RESEARCH STUDY OF AN AIRCRAFT - CONTAINED RADAR ZERO-ZERO LANDING SYSTEM

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ABSTRACT

Two rapid scan radar/display techniques (P^3I & CBRS) were developed and demonstrated, utilizing the benefits of each technique to provide a pictorial, vertical, linear perspective display of a landing area and the terrain preceding and surrounding it. The resulting display is intended to be used in the performance of aircraft landings under conditions of zero visibility and zero ceiling and without the need for cooperative ground equipment.

An introduction to motion cue guidance is developed as a technique for designing radar, comparing radar/display results with normal vision, gaining insight into the experience of landing an aircraft, and drawing attention to the difficult task of visual landing as well as possible solutions which could lead to an instrument landing capability "better than visual".

This final report, together with addendums and references, can be used as a concept design guide for low level flight, specifically, approach to landing and touch down.

ACKNOWLEDGMENTS

This study program was monitored by, and coordinated with, Gilbert Robinson and Robert Griffin, Guidance and Control Systems Branch, Full Scale and Systems Research Division, NASA-Ames Research Center. Lockheed Electronics Company personnel who have contributed to this program include: Homer B. Tilton, Frank S. Gutleber, Robert W. Neher. George H. Boehm, Ansel H. Leffel and John F. Dey.

VOLUME II

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

1. SUMMARY

This Final Report (Volume I), together with the Addendum (Volume II), is the first attempt by the Airborne Radar Program personnel of Lockheed Electronics Company to assemble in one published report the concept of using long wave (radar) vision to produce a pictorial, linear perspective display/radar through techniques such as the P^3I (Processed PPI) and CBRS (Cross Beam Raster Scan). This report, as outlined by the summary, is intended as a concept design guide for low level flight, specifically, approach to landing and touchdown.

The intent of this study program, as defined by Contract NAS2-4091[1], is "to conduct a study of the feasibility of a radar display/system for landing of aircraft under conditions of zero visibility and zero ceiling without the aid or need of ground instrumentation." The display desired was pictorial – a radar display which would present the pilot the available landing cues in a form with which he is already familiar. <u>These objectives have been met, as demonstrated by Figures 7, 58, and 59.</u> Figures 58 and 59 are examples of the radar/display achieved by use of a rapid scanning antenna (the Variable Ridge Scanning Antenna) and circuitry for processing the radar data into a pictorial perspective display, described in Sections 6 and 7. Figure 7 is from the first flight-demonstration film of the Lockheed Electronics Company P^3I radar, accomplished by optical processing (rather than the electronic processing of Figures 58 and 59) of movies of the Lockheed Rotor Blade Antenna Radar. Although the radar data for Figure 7 was real-time flight data, data processing took place in the laboratory. It is recommended that a follow-on phase be pursued to implement a real-time flight demonstration of this radar-derived perspective display.

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[1] <u>Note</u> - References are listed in Section 9, Volume I.

Sections 2 through 4 develop the problem to be dealt with in the main body of the report. The radar/display objectives, concepts, and definitions are presented. The P^3I and CBRS radar/display techniques and a method for registration are developed.

Section 5 is an introduction to motion cue guidance as a technique for designing radar, comparing radar/display results with normal vision, gaining insight into the experience of landing an aircraft, and drawing attention to the difficult task of visual landing as well as possible solutions which could lead to an instrument landing capability which is "better than visual."

Included with this report are two Addendums which excerpt two unpublished reports prepared in 1962 and 1965. These addendums, as well as several of the references, are intrinsic to a full understanding of the concepts presented and of current and future design planning.

ADDENDUM I

Excerpts from: January 13, 1965, Letter Report, LRSTP Project 4-461-60, to Department of the Navy, ONR, Washington, D.C., Code 461; from D. W. Young

INTRODUCTION

The LRSTP Project report is an important reference which was not published; excerpts from it are included below. There are quotations from 14 references, and 19 comments by the author concerning the usage of a display such as the P^3I and CBRS vertical display/radar as examples of long wave vision. The majority of the text relates common experience with requirements for resolution, attitude sensitivity, texture, beamwidth, and other parameters used to describe long wave vision. While these excerpts were prepared in 1965 and some changes have occurred, the report provides an excellent base from which to gain insight into progress leading to the Final Report.

Reference (1)
Charles A. Zweng and Allan C. Zweng, "Radio and Instrument Flying", 18th Revised Edition, Pan American Navigation Service, 1963

THE AIRPLANE OUT OF CONTROL

p. 34 As a general rule, the airplane will get out of control only in a turn, or more especially, in a downward spiral.

RECOVERY FROM A SPIN
(1-2-3 Method)

p. 39 One factor that is often overlooked during the discussion of spins and the recovery from them during instrument flight is the fact that the greatest danger to a pilot flying on instruments is not a spin but a tight, high-speed, diving spiral. In an attempt to correct for excessive airspeed present in a "graveyard spiral", an inexperienced pilot pulls back on the stick which has the effect of increasing the bank and tightening the spiral with a resulting increase in the airspeed rather than the expected decrease.

ATTITUDE METHOD

p. 39 Individual use of the controls in the 1-2-3 order has a very slow effect on an airplane in this position (graveyard spiral). When the gyro-horizon is being used, a "graveyard spiral" is easily recognized as the miniature airplane will be positioned well below the horizon bar and in a steep bank. This gives an instantaneous visual indication of the dangerous attitude of the airplane and also shows the proper method of recovery: returning the airplane to straight and level flight by the properly coordinated use of the controls.

p. 40 While the "full panel" method is undoubtedly easier and the period of time required to learn to "fly on instruments" is considerably less when use of the gyro-horizon is allowed, the FAA does not at the present time allow the use of the gyro-horizon during the flight tests (part of: D.Y.) for an instrument rating.

Reference (2)
"Federal Aviation Regulations for Pilots", Pan American Navigation Service, September 1964.

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p. 18 61.37 Instrument rating: skill requirements, (2) Phase II-Instrument flying test: (i) Straight and level flight, using <u>needle</u>, <u>ball</u>, <u>and</u> <u>airspeed</u> <u>only</u>. (ii) Turns, climbs, and descents, using <u>needle</u>, <u>ball</u>, <u>and</u> <u>airspeed</u> <u>only</u>.

ERRORS IN TURNS

p. 40 This slight precession during a turn will introduce a "bank" error causing the instrument to indicate slightly less than the actual degree of bank during a turn, and in some cases after level flight has been resumed, it may even indicate a slight bank in the opposite direction. This error rarely exceeds 6° and consequently is so small that it will cause no serious error in the control of the airplane.

The same effect causes the horizon bar to dip slightly below its normal position for level flight. The "pitch" error is slight and the horizon bar is seldom displaced more than its own width (perhaps 2.5°: D.Y.)

INSTRUMENT LANDING SYSTEMS

p. 77 ILS Localizer: The pointer is very sensitive and will give a full-scale deflection when the aircraft is 2.5° to either side of the on-course. If the pointer is no farther off center than one-quarter scale, the aircraft will land on the runway (a width of 1.244° error width capability with safety: D. Y.)

Since the glide path course is much sharper than the localizer course (less than 1.5° from "full up" to "full down" on the instrument), it is necessary that the aircraft be aligned accurately on the glide path at some distance from the field. Only very minor corrections are possible near the ground. (L.A. International reports 1.4° full scale width of glide slope.)

MAKING A GCA PRECISION APPROACH

p. 50 GCA (Radar Ground Control Approach) radar has two beams, each 20° x 0.5°. (Two scans/second limits the turning rate of aircraft: D.Y.)

p. 51 Heading corrections are given in three digits. (Commander Robert F. Lawson of the Office of Naval Research, Pasadena, California, indicated the experienced controllers usually provide him 2° heading changes and he has to interpolate on his gyro in the aircraft because his gyro is calibrated in 5° increments.) (I think most gyros are calibrated in 5° increments: D.Y.)

Reference (3)
Neil D. Van Sickle, "Modern Airmanship", D. Van Nostrand Company, Inc., June 1961.

INSTRUMENT FLYING

p. 510 11.39 TACAN Bearing Information: The airborne receiver measures the time differential between the phase of the signal, giving bearing information which is <u>accurate to within ± 1°</u>.

TECHNIQUE AT NIGHT

p. 359 Many pilots prefer to land on lighted runways without using landing lights: When haze, smoke, rain, snow, or fog obstruct visibility, reflection renders landing lights more of a hinderance than a help ..... By maintaining a careful approach speed, and by looking well ahead of the aircraft to improve depth perception, round-out and landing will present no serious hazard. A little power carried through roundout and touch-down will insure more consistently smooth landings.

FINAL APPROACH CUES

p. 320 Aiming Point

The point toward which the aircraft is settling will be termed the "aiming point". To a pilot moving straight toward an object, it appears to be stationary. It does not "move". The aiming point is no exception. But objects in front of and beyond the aiming point do appear to move as the distance is closed, and they appear to move in opposite directions.

p. 321 Altitude Clue 1

During a constant glide, the distance between horizon and aiming point will appear constant (no relative motion). If the aiming point that should result from a glide has been determined but the distance between the point and the horizon appears to increase, then the glide will carry the aircraft farther than first thought, and the real aiming point is farther down the runway. Decreased distance below the horizon indicates an actual aiming point short of desired. This is one way you can determine whether your glide is correct or not. Many pilots do not realize that they use this technique, but they do.

Altitude Clue 2

A second related cue as to correct height on final approach is in the apparent shape of the runway. The importance of runway shape becomes apparent when a pilot who is used to operating from a runway of normal dimensions encounters a grass field or runway that is very narrow or very wide. He will have trouble with his glide altitude until he learns to accommodate to the new proportions.

Use of Clue 1 & 2

In a project undertaken at the University of Illinois, students were briefed on use of the aiming point and runway shape cues. They were intoduced to use of these cues in a modified Link instrument trainer as a flight simulator. After practice in the simulator, the experimental group of students required 61% fewer practice approaches in actual flight practice of landing approaches; and they made 74% fewer errors during the flight phase of the operation.

Obstacle Avoidance

What about poplar trees and power lines? Treat the obstacle as another possible "aiming point". If it does not move in one's angle of vision, that is what it is. (Some pilots call the "aiming" point the "crash" point; perhaps the latter term is more appropriate here.) If the obstacle moves up toward the aiming point, you will not get over it in your present glide. <u>If it moves down away from the horizon and aiming point, even to a barely noticeable degree, you will get over it without changing the glide angle.</u>

Reference (4)
Air Transport, Category 2 Approval, Aviation Week & Space Technology, January 4, 1965, p. 29

An approach will be considered to be successful if, when the aircraft reaches the 100 ft. altitude, it is in trim so it could continue and land, the indicated airspeed and heading are suitable for a normal flare and landing and the aircraft is positioned within the lateral confines of the runway extended. Also required is that the deviation from the glide slope does not exceed 75 microamps, as measured by the ILS indicator (corresponding to one dot displacement from center on newer instruments) and that no unusual roughness or excessive attitude changes occur after aircraft has left the middle marker.

(Lloyd Allen of D. Young & Assoc. found 75 microamperes provided a one dot deflection on a U.S. Army indicator 1-101c, and L.A. International Airport, California suggested full scale on the ILS glide slope was $\pm$ 0.7°. One dot to either side of the small circle in the middle, or 75 microamps would provide a corridor of 0.56° width.) (Business Week, Dec. 19, 1964, McGraw Hill, p. 96: Category II: 100 ft. ceiling and 1200 ft. visibility down runway.)

Reference (5)
Department of the Army Technical Manual (TM 55-1520-211-10), "Operator's Manual Army Models UH-1A and UH-1B Helicopters", Dated February 1, 1963, changed June 1, 1063, changed October 1, 1963

Chap. 10
p. 2-4 Section II, All Weather Operations

For all pitch and bank corrections, utilize the attitude indicator. Do not exceed a one bar width pitch correction for minor altitude changes and limit the angle of bank in turn to 15°.

Instrument approaches are easily flown in this helicopter. Before commencing the approach, have the attitude indicator properly set.

p. 2-2 Vertical take-offs are not compatible with and are not recommended for instrument conditions.

Instrument climb: Excerpt: Any pitch attitude corrections should not exceed one bar width. The angle of bank should never exceed 20 degrees.

Instrument Cruising Flights: As previously mentioned, the constant diligence required to conduct instrument flight produces pilot fatigue. This is especially true on long missions...Upon establishing the recommended cruise speed, the attitude indicator should be set for a nose level indication. Thereafter, any pitch or bank corrections should be made utilizing the attitude indicator. <u>Pitch corrections should not exceed one bar width.</u>

Instrument Cruise: Instrument cruising flight at speeds less than 60 knots IAS is not recommended. The aircraft handling qualities at speeds less than 60 knots (because of power required characteristics) are not compatible with instrument flying.

p. 2-3 Maximum (Autorotative) Descents:

Autorotations are not difficult on instruments. However, due to the high rate of descent, they are recommended for emergencies only. Assume a one bar width nose high attitude, and maintain directional control with the foot pedals. The airspeed will gradually decrease to 60 knots IAS. Approximately a one bar width nose high attitude will give this speed, which should be maintained until visual contact is made and a reasonable 2,000 to 2,400 feet per minute rate of descent...and so on...(crude measurement of one line width indicated about 2.0° pitch according to D.W. Young.)

p. 2-1 Co-pilot is required.

p. 2-1 However, precision instrument flying requires considerably more instrument monitoring than required in conventional fixed wing aircraft. Any pilot, however, can conduct safe instrument flights in this helicopter if he is proficient in basic instrument flying and applies the proper technique and procedures. Much greater use of attitude indicator is required. Instrument flying is not to be attempted without an attitude indicator.

Reference (6)
Wesley E. Woodson and Donald W. Conover, "Human Engineering Guide for Equipment Designers", Second Edition, 1964, University of California Press.

VISUAL CUES (motion)

p. 2-139 One of the major visual cues used by pilots in maintaining precision ground reference during low-level flight is that of object blur. We are acquainted with the object-blur phenomena experienced when driving an automobile. Objects in the foreground appear to be rushing toward us while objects.....etc.

At a relative angular velocity of 3 degrees per second an object out front will appear to be almost stationary and at 10 degrees per second it will begin to blur almost beyond recognition. (Incidentally, 3°/second is a standard instrument procedure turn: but this is not to be confused with the 15° required to get the turn, since the 15° attitude change is very easy to detect, certainly easier than rate of change of angle: D. Young)

p. 6-47

PERCEPTION OF THE VERTICAL

Perception of the vertical -- that is, the direction of action of normal gravitational forces -- and of one's postural relation to that vertical are important aspects of orientation...etc...Both visual and postural vertical are largely determined by joint action of visual and gravitational forces. Visual "forces" affecting the judgment are those which spring from the alignment (or lack of it) of the visual framework or main lines of visual space with respect to the true vertical position. Gravitational (g) force on the body is the vector sum of forces imposed on it by acceleration and normal gravitation. This resultant force exerts a very powerful influence upon our orientation and/or perception of the vertical, which is in the direction of action of the resultant g.

p. 6-47 PERCEPTION OF THE VERTICAL (Postural Tilt)

The smallest degree of body tilt in any direction which can be detected has been found for a group of pilots, ranging from less than 1 degree all the way up to 14 degrees. The average threshold was between 2 and 3 degrees, with that of backward tilt roughly 1/2 degree higher than thresholds for tilt in the other quadrants. Elimination of visual cues raises these thresholds. With poor visibility, banks of 10-15 degrees in aircraft may not be recognized by an individual in flight.

Laboratory tests, using a "tilt chair" which can be operated by the experimenter or by the subject himself while seated in it, have shown greater sensitivities than those observed under conditions of flight.

ORIENTATION

p. 6-44 We maintain our orientation to and equilibrium in the world about us by a combination of visual and auditory information, data provided by action of the semicircular canals...etc. Abnormal or conflicting conditions make discriminations more difficult, and sometimes cause serious errors of perception....(curve in figure shows motion threshold of about 4.5 degrees/second/second for 2 seconds and 1.5 degrees/second/second for times exceeding 16 seconds.

Reference (7)
George E. Passey, "The Perception of the Vertical", Journal of Experimental Psychology, Vol. 40, 1950, School of Aviation Medicine and Research Naval Air Station, Pensacola, Florida, and the Tulane University of Louisiana.

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p. 742 The determination of the vertical is a joint function of the postural and visual factors and best judgments are rendered when the two sets of factors complement each other. In the present experiment the compromise was weighted in the direction of postural factors, but this might easily be an artifact of the experimental procedure and the equipment employed. (Curves suggest 1° tilt of visual would cause little error in vertical judgment but the data was taken in 5° increments of tilt. 5° visual tilt caused error in judgment of as much as 20°: D. Young.)

Reference (8)
Gilbert G. Robinson and Norman S. Johnson, "Subsystem Requirements for an Airborne Laboratory to Study Zero-Zero Landing Systems", Ames Research Center Moffet Field, California, October, 1964.

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p. 13 It appears that most aircraft autopilots that are accurate to 1° will be adequate for the attitude sensing subsystem for the zero-zero landing system.

Reference (9)
Ross A. McFarland, Ph.D., "Human Factors in Air Transport Design", McGraw-Hill Book Company, Inc., 1946.

ACCELERATION AND MOTION

p. 361 Thus, in the absence of visual cues, neither pilot nor the passenger is aware of the extent to which the plane is tilted. This difficulty soon became apparent in the early days of instrument flying; sensitive indicators had to be developed to compensate for errors arising from such sources. (Mr. McFarland said earlier, "In flight, however, an airplane may be banked 10 to 15 degrees or more before the average person may be aware of it": D. Young.)

p. 365 Aviator's vertigo can be prevented only by the use of visual cues, which under the circumstances are the pilot's only way of orientating himself correctly.

Reference (3)
Neil D. Van Sickle, "Modern Airmanship", D. Van Nostrand Company, Inc., June 1961.

HELICOPTERS: FLIGHT MANEUVERS

p. 692 Hover is the sustained motionless flight of a helicopter. It implies zero airspeed and constant altitude and heading. The pilot uses the right hand to control the cyclic stick...and also anticipate horizontal movement of the aircraft.

(On day with no wind anticipate horizontal movement by observing attitude: D. Young.)

Hovering is a basic maneuver because forward flight is started from the hover, and the approach ends in the hover, prior to touchdown (true for visual flying, not instruments: D. Young).

Reference (10)
Charles A. Zweng, "Private Pilot Helicopter Rating", A study test and guide to the written examination, Pan American Navigation Service.

FLYING THE HELICOPTER

HOVERING

p. 75 The pilot has the same problem in hovering, as in straight and level flight, since the attitude of the helicopter is the governing factor which determines the aircraft's movement over the ground. Though the attitude required to hover varies with the wind conditions and balance, there is still an attitude (both pitch and bank), which can be found by experimentation. If this attitude is maintained the pilot can keep the aircraft hovering over a spot. Once the attitude is determined, the pilot can notice any deviation and make the necessary corrections prior to the helicopter moving off the spot.

Reference (11)
Instrument Flying for Helicopter Aircraft, Department of the Air Force, AF Manual 51-13, 1962 (This manual supersedes AFM 51-13, Instrument Flying Techniques and Procedures for Helicopter Aircraft, 10 November, 1959.)

HELICOPTER INSTRUMENT FLIGHT LIMITATIONS

p. 1 The use of conventional aircraft instruments limits slow speed flight, except for instrument takeoff, and prohibits hovering flight. (Minimum speed for UH-1A and UH-1B is 60 knots according to Army Technical Manual: D. Young.)

p. 2 The slow airspeed of the helicopter with its resultant large drift correction angles makes radio navigation difficult. A 30° drift correction is as common to the helicopter as 10° is to conventional aircraft. Flight in high winds (25-40 knots) will render time-distance equations and radio range orientation procedures difficult if not impossible to use.

p. 3 The use of conventional aircraft instruments in helicopters prohibits "partial panel" instrument flying in any measurable turbulence. The turn needle fluctions excessively and gives false indications of turning. Loss of the gyro-stabilized attitude and directional indicators during flight through turbulence would cause the pilot to be unable to control his aircraft. (The TM manual for the UH-1 indicates the gyro will last long enough after engine failure to perform an auto-rotation letdown: D. Young.)

ATTITUDE CONTROL

p. 8 Definite pitch attitude changes are accomplished by changing the "pitch attitude" of the miniature aircraft definite fractions, or multiples, of the thickness of its wings or fuselage dot. These corrections are generally referred to as bar widths or fractions of bar widths. (The calibrated figure on page 8 suggests one bar width is approximately 2.5° pitch attitude change. <u>One bar up to one bar down would give a total attitude change of 5° suggested as maximum change for the UH-1</u>: D. Young) (Any change less than 1/2 bar width, 1.25°, would be hard to see.)

CROSS CHECKING THE INSTRUMENTS

p. 12 Lag in the performance instruments certainly need not interfere with holding or smoothly changing the indication of the attitude and power indicators...

Thus, smooth helicopter control, resulting from efficient reference to the control instruments, simplifies the task of interpreting indications of the performance instruments... A useless "chasing" of instrument indications can easily result.

p. 12 The attitude indicator is probably the only instrument to which attention may be continuously devoted for any appreciable length of time. Approximately 10 seconds may be needed to accomplish a common attitude change such as that required to establish a turn. During this 10-second period, you may need to devote your attention almost exclusively to the attitude indicator to insure good attitude control. Also, <u>the attitude indicator is the instrument that is checked the greatest number of times</u>.

INSTRUMENT TAKE-OFFS

p. 27 Prior to attempting a normal instrument takeoff you must remember that the flight instruments cannot register direction of flight nor airspeed in other than forward flight. Therefore, control techniques during the initial takeoff phase must insure positive measures to prevent inadvertent sideward or backward flight or loss of altitude.

Reference 12
Department of the Army Technical Manual (TM 55-1520-211-10), "Operator's Manual Army Model UH-1A and UH-1B Helicopters", Dated: 1 Feb. 1963.

Chap. 10
Sec. II

INSTRUMENT TAKE-OFF

p. 2-2 The attitude indicator, heading indicator and torque meter are primary for instrument take-offs.

After positioning the aircraft on a level... adjust the horizon bar of the attitude indicator so that the <u>miniature airplane will appear approximately two bar widths above the horizon bar</u>....

With a steady, smooth motion apply collective pitch until five pounds of torque more than that required for hovering is obtained. As the aircraft leaves the ground, position the cyclic so that the miniature airplane will appear one to two bar widths below the horizon bar. Maintain directional control (heading) with the pedals until airspeed increases, generally (30-40 knots) then transition....

As airspeed reaches 70 knots the pitch attitude is adjusted to the climbing attitude (miniature aircraft on the horizon bar).

(Thus, the attitude is changed approximately 10° or 4 bar widths during take-off and adjustment to climb attitude: D. Young.)

Reference (13)
Dr. M. D. Havron, Human Sciences Research, Inc., prepared a report for the Systems Research and Development Service, Federal Aviation Agency, under contract No. FAA/BRD-40. "Information Available from Natural Cues During Final Approach and Landing, HSR-RR-62/3-MK-X, March, 1962".

EARTH VELOCITIES & HUMAN CAPACITIES COMBINED

p. 22 For reliable steering, it is highly desirable that movement be detectable in all cases; or if this cannot be accomplished, that it be detectable in the great preponderance of instances. As rough estimates, and to provide an even figure, we take 10 min./sec. (1/6th degree/second) as a super threshold value for daylight conditions and 30 minute/second (1/2 degree per second) as a sufficient value to permit detection of movement at night. It is assumed that pilots can reliably detect movement of these rates under most conditions encountered in contact flight where effects of turbulence, vibration, windscreen distortion are not considered.

p. ii SUMMARY

Results must be considered tentative because human factors data available for estimation of thresholds were collected under laboratory rather than field conditions. Further, quantitative values of thresholds for perception of movement vary widely among reports in the literature.

p. iii A better understanding of extra-cockpit cues available and how pilots can best use them should have importance for pilot training, for better understanding of conditions conducive to false guidance and optical illusions, for better and more economical design of Automatic and Manual Landing systems and for flight safety.

Reference (14)
Business Week, McGraw-Hill, page 96, "How Airlines Will Outwit the Weather", December 19, 1964.

In 1964, low ceilings cost carriers $70-million in revenue.

January, 1964

Mr. William Dehnke, FAA helicopter flight examiner, owner of Helicopter Center (Van Nuys, California) and helicopter flight instructor, indicated he could fly a helicopter often times when fixed wing aircraft could not fly due to IFR minimums and he further indicated he could fly with very little visibility and only visibility almost straight down, as long as he knew the terrain very well and particularly the route to be flown. Mr. Robert Angstadt, vice-president of Chicago Helicopter Airways also indicated little visibility was required if the route and the terrain were familiar. D. W. Young has seen Mr. Dehnke hover an aircraft with the use of only peripheral vision, and hover very well.

D. Young statement: I believe it has been shown in the past (but the details are classified) that aircraft can be automatically controlled quite well in the terrain following mode with no better resolution than 1° to 0.5°. I believe both drones and manned aircraft have been controlled automatically and precisely in the terrain following mode (reference Cornell Aeronautical Lab, Army & Air Force work).

(Comments on the preceding references are made by the author below. The effect of the references on the design of radar is emphasized, particularly resolution and texture requirements.)

1) The long wave visual cues obtained from the radar must be sufficient to perform turns and adjust attitude safely. A relative attitude threshold of 1° and a turning threshold rate of 1°/sec., with blur turning rates of 10°/second, will perhaps be satisfactory. The cues for attitude and turns are the most important cues for performing cruise, climb and descents.

2) Since a helicopter can be operated IFR on take-off, climb, cruise and descent, but not hover or final landing and touch-down, the radar must provide only sufficient cues for hovering and for the transition from hover to forward flight to actually utilize the helicopter under zero-zero (zero visibility, zero ceiling conditions). Incidentally, the normal IFR take-off is like a near maximum performance take-off (AF manual, Ref. 11, p. 27). If the radar would provide hover capability, the IFR take-off could begin from a hover (normal VFR takeoff) which would be much safer takeoff.

3) 60 knots is now the minimum, safe IFR flying speed for the UH-1 (Ref. 5). A radar which would provide hover capability at low and high altitude would greatly increase the utility of the helicopter.

4) If attitude can be adjusted accurately enough and motion cues and range rates are sensed well, it should be possible to make a zero-zero landing through use of the radar. This is true of the helicopter and certainly the fixed wing aircraft. Certainly a fixed wing and perhaps the helicopter can be landed without a radar altimeter, but the altimeter could provide good supplemental "backup" information. The references and other notes suggest this may be done with a 1° beam scanning radar.

5) It is reported that a colonel at the NASA facility at Elington Field, Texas, hovered a UH-1 with only a gyro for short periods without wind. While it is obvious this was not a practical hover maneuver, it was an important demonstration of the utility of attitude sensing. (References 1, 5, 8, 3, 11,

12, describe the accuracy and importance of attitude, where one bar width is assumed to be approximately 2.5°).

6) What about the image to be seen on the display? The emphasis given here is that texture is a primary element to be sensed for operational performance of the aircraft, and the image is of secondary importance. The only image discussed is perhaps a recognizable pattern which is the runway. Target identification or image identification is more difficult to do and requires better resolution than that required to land an aircraft under zero-zero conditions. Target identification is certainly more difficult than target detection. If a pass over a Viet Cong trail one night with a 1° scanning beam showed a clear trail and the next night showed something on the trail, target detection would be close to target identification or recognition, but this is a special case and a useful one. A higher resolution radar would provide better target identification capability, but not necessarily better target detection capability.

7) Prior knowledge through familiarity with terrain can be very useful (professional pilot statements following reference 14). While emphasis has been on the 1° scanning radar, the 0.3° to 0.1° rotor blade antenna resolution would be very useful in target identification, not just target detection. Fire control would be a seemingly natural consequence.

8) Few people stop to realize what 1° is. The moon is approximately 2,160 miles in diameter and its mean distance from the earth is about 238,857 miles. The moon subtends an arc of approximately one-half degree (0.52°). 1° is the approximate angle subtended by the width of the thumbnail (where the skin is attached to the finger nail, about 1/2 inch wide) as observed by the eye and the arm fully extended at right angles to the body and shoulders back. It is probably more important to experience 1° (or portions thereof), as you drive down the freeway, or fly a fixed wing or rotary wing aircraft than to

experience what a particular model radar-display combination may provide. The logic for and the technique for processing the basic signal from the radar may well be more responsible for limiting the recognizable features of targets shown on a particular radar-display combination. If the information content is sufficient from a radar, an image of sufficient quality can be presented on the display.

9) I would say after a review of the references enclosed, that a radar with 0.5° to 1.0° or perhaps 2° capability would be more than adequate for IFR approaches to the runway with an approach quality of GCA or ILS and yet using only the self-contained equipment on the aircraft (not ground instrumentation). And that this radar would be sufficient for approach to Category II (100 ft. altitude and 1200 ft. visibility down runway). The next phase is speculative. However, 1° will identify individual light fixtures on the side of the runway (aircraft on other side) down the runway about 1,400 ft. and if the observer in the aircraft is at one end of a 10,000 ft. runway, a 1° resolution will just blend the runway lights on either side of the runway in the apparent middle of the runway at a range of 10,000 ft., and this is a very effective linear perspective. It is my opinion that the final phase of the landing, including touchdown, would be just as described for a night landing in Reference 3, p. 359. (This situation assumed the light fixtures were 100 ft. apart down one side of the runway and the spacing between the lights on one side of the runway to the other side, was 170 ft., which are conservative values.)

10) Better resolution will provide more accurate landings but 1° resolution will permit zero-zero landings.

11) A very important cue for alignment with the runway (particularly with some crab angle due to a cross wind) will be the relative motion of objects (light fixtures, grass, stubble, buildings, etc.) on one side of the runway compared with the motion of objects on the other side. It is expected that while

motion may be seen easily with the radar (1°/sec. or less), relative motion, where two series of objects are moving at different rates, should be easily sensed (differential rate).

12) While it is distracting to fly with a dirty windshield, it can be done, and it has been observed in the laboratory that obstacle motion can be sensed even in the presence of cross-coupling between one antenna and the other because the cross-coupling (apparent obstacles) signals do not move on the display. This is not a big problem because the cross-coupling can be eliminated, but this is another interesting characteristic of the system. "For reliable steering, it is highly desirable that movement be detectable in all cases"; a statement by Dr. Havron, Reference 13, p. 22.

13) Dr. James W. Miller, Office of Naval Research, said, "The point was made that <u>we must use man for tasks at which he excels</u>." This quote was from proceedings, Visual, Display, and Control Problems Related to Flight at Low Altitude, Edited by Dr. James W. Miller. There is a good possibility, suggested by laboratory experience, that a pilot can judge his alignment on a row of wooden telephone poles, as presented with a 1° beam, much better than 1°. It has also been experienced at this laboratory that assuming no change in range, that the ability to sense a change in position of a target displaced on a 1° resolution raster scan, two dimensional display with intensity modulation is some K times better than the beamwidth of 1°, where K may be 2 to 5. This perhaps unexpected improvement is because no matter what the size (but much larger than eye resolution) of the high intensity disk on the display which represents a point target, the definition or sharpness of the edge of the disk is the important factor and not the width of the disk. As an extreme example, examine what would happen if a 10° beam was used to display on a raster, a single target, and the intensity is controlled by a trigger rather than an analog function. If the signal strength did not change (and, of

course, it will to some degree) as the target moved, the eye would probably observe the displacement of the target on the radar display just as quickly as optically. Again, the signal logic and technique for processing the signals from the radar are extremely important. And these signals should be processed to "use man for tasks at which he excels."

What is the ability of the observer (man) to perform the function of "monopulse"*? I find it amazingly good. The method of improving radar resolution for guidance systems by comparing (for a single target) signal strengths of two beams (when one target gives each beam the same signal strength it is exactly in line between the beams) has been done for long time. The conical scan method is the same thing using time sharing of the same beam. Simultaneous lobing or sequential lobing are all similar things. However, it is important to compare the signals from two (or more) beams at either the same instant or nearly so because the effective reflectivity may change or will change with time. With the electronic scan antenna developed here, the time between two adjacent beams is only 40 μs, an essentially "monopulse" time. If one point target is located between two beams shown on a raster mosaic display (the beam is continuously scanned but the transmitter is only operated at 24, 000 pulses/ second) and if the intensity modulation is an analog function, it is evident that when the target is exactly between two beams that the intensity is the same on the two adjacent squares which represent the beams on the mosaic and the crispness of the difference in intensity with target displacement off of the center line between the lines is greatly dependent on the function of display brightness versus signal strength.

14) I strongly suspect that many of the cues required for flight and provided by radar (not all of them by any means), i.e., many of the very important cues, are not a function of, or are very soft functions of, beamwidth or long wave acuity.

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* Introduction to Monopulse, Donald R. Rhodes, McGraw-Hill Book Co., 1959.

15) What must be the ability for depth perception? Motion cues have much to do with depth perception and landings can certainly be made using T.V., one eye, etc., but in hovering a helicopter some specific estimates of change in range are certainly desirable, if not required.

16) Take the following situation: Man approximately 20 inches wide, standing up under rotor tip, rotor turning up at pressure necessary for hover, but collective down, some background is present at 1/2 mile on the horizon all the way across a 30° field of view. Put into hover using the horizon as indication of attitude, using man on ground as key to helicopter position (both altitude and range). Man subtends about 10 beams: If the helicopter moves away from man 20 ft. (from rotor tip), the number of beams which represent the man in azimuth will be 10 beams and if the helicopter moves closer, say half a rotor radius (or 10 ft.), the man will subtend 20 beams.

How little range change could be discerned?

The man (20" wide) is again standing up under the hovering helicopter at the rotor tip and subtends 10 beams. When a change of one beamwidth is sensed, which would change 10 beams to 11 beams, it can be shown that a range change of 1.82 ft. occurred. This range increment is a function of the number of beams subtended for a given range for a given target.

This particular situation suggests a change in range of 1.8 feet can be sensed.

17) What scatterers are necessary for hover?

Certainly texture is very important. Range change is easiest to see if the target or terrain subtends a large angle (many beams). It may be easier to land in a very small field surrounded by big trees than landing on a large airport with little or no obstructions, or scatters such as grass, stubble, etc. which outline the landing strip.

18) Where obstacle detection and the resultant motion cue and other cues end and where obstacle identification begins is certainly difficult to define. Runways are probably sufficiently described for identification with an azimuth resolution of 2° (see enclosed radar picture), and while motion cue of a few lines or few dots (reference NASA landing simulator using only few line contact analog) may be evident, very few lines or few dots are not going to give much identification. (You probably couldn't distinguish a man from a post, but perhaps you could tell if you were going to hit the man or post.)

19) Some of the copies of this paper will enclose a PPI and vertical display of a runway made with a 2° beam. The PPI is a copy of the cathode ray tube and the vertical photograph is a projection, similar to work shown in previous reports, Interim and Final Reports, Nonr-4032(00). I found the pictures surprisingly effective.

The runway is part of an abandoned airport about one mile south of Orange County Airport and on the edge of an earthen dam at about right angles to the dam. There is a helicopter at one end of the runway. The PPI was taken at about 100 ft. and the projection indicates about 250 ft. altitude. The range is one-half mile from the center of the PPI to the edge. There is no doubt that alignment could be maintained on this runway with this display.

The Viet Nam runway, outlined by large trees shown on page 40 of the January 1965 National Geographic, would provide an even more highly contrasted radar runway presentation than the one enclosed.

ADDENDUM II

Excerpts from: Three-Dimensional Radar Final Engineering Rpt., No. 301-5, May 10, 1962, a subcontract under Contract Nonr-1076 (00) by David W. Young & Associates, Inc., A JANAIR Project.

INTRODUCTION

Excerpts from Report 301-5 have been included as a reference because there was very limited distribution of the report. Although the report was written in 1962, it was the first final report on:

1) P^3I, (then called synthetic sweep) concept and circuitry
2) Registration, then called interferometer sweep and sweep comparator
3) Nonambiguous interferometer techniques with largely spaced antennas
4) Crossed Beam compared to P^3I
5) Variable Resolution as a function of pilot eye movements

The techniques included in the excerpts are intrinsic to current and future design planning.

The interferometer sweep is used to avoid obstacles or detect errors in the synthetic sweep. In the advanced system a constant comparison is made between the two sweeps by the sweep comparator.

3.2 The Interferometer Vertical Sweep Generator

A. Introduction

The degree of terrain avoidance capability depends largely on the effective generation of the vertical sweep for the vertical display.

B. A Review of the Interferometer System

A difficult problem of the 3D radar design was to obtain a high elevation data rate at low cost. The solution used was to measure the vertical angle with monopulse and the azimuth angle with an electrically scanning beam.

The unique portion of this radar (while rapid azimuth scanning is not commonplace) is the method in which elevation information is sensed. Phase ambiguities are used to advantage to cause the multiple beam. The system has multiple elevation beams (all adjacent beams being opposite in polarity) for the vertical display. Phase comparison takes place at microwave using a widely spaced antenna array of many wavelengths separation. Targets that lie in one plane of elevation must be received at monotonically decreasing elevation angles (the angle cannot reverse since the radar cannot see the other side of a major obstruction). To properly display these on the vertical display requires a sweep with a nonlinear time base corresponding to angle. This can be accomplished by counting the rate and number of beams from some specific angle toward the horizon. See Figure 1.

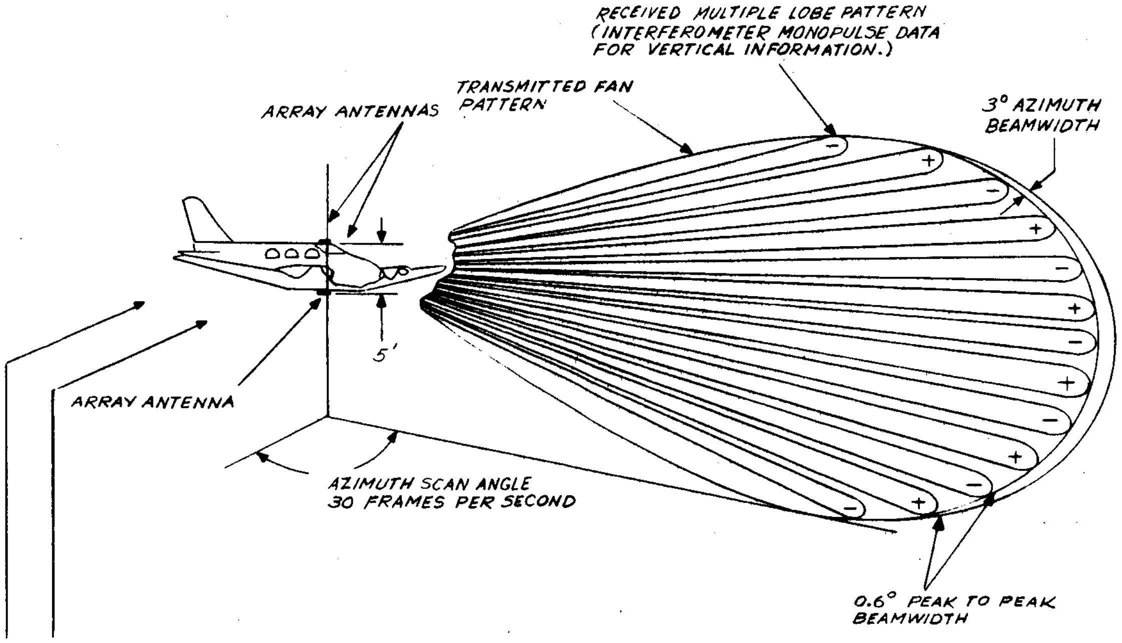


Figure 1. Three Dimensional Radar Antenna Pattern Geometry and Block Diagram

The rate at which these beams alternate from plus to minus determines the sweep speed. The number of beams determines the sweep length. For example, if the aircraft rolls to the left, the left side of the vertical display is lengthened from normal and the right side is shortened. The result is that the real world horizon and the display horizon roll together.

C. The Interferometer Derivations

The phase comparison technique determines the radar return arrival angle. Consider two vertically spaced receiving antennas whose outputs are compared in phase. Radar energy returning from above or below the boresight of the two antennas (the center line of the two antennas or the aircraft longitudinal axis), will arrive at one antenna before the other. Difference in time of arrival causes the output of one antenna to lead or lag the output of the other. Taking one antenna as a reference and θ as the angle off boresight, the expression for the phase shift in the other antenna is:

$$\emptyset = 360\ (D/2) \sin\theta$$

where D is given in wavelengths

or

$$\emptyset = (D) \sin\theta$$

where D is given in electrical degrees of antenna spacing.

The voltage output from the system phase detector (relative to the peaks and nulls) can be described by:

$$V = \sin\emptyset$$

Thus, $V = \sin\emptyset = \sin(D \sin\theta)$ (See Figure 2.)

The voltage output from the phase detector would then swing smoothly from positive to negative voltages as a target is gradually moved away from the boresight axis. These voltage swings are caused by the multilobes of the interferometer pattern of the two antennas.

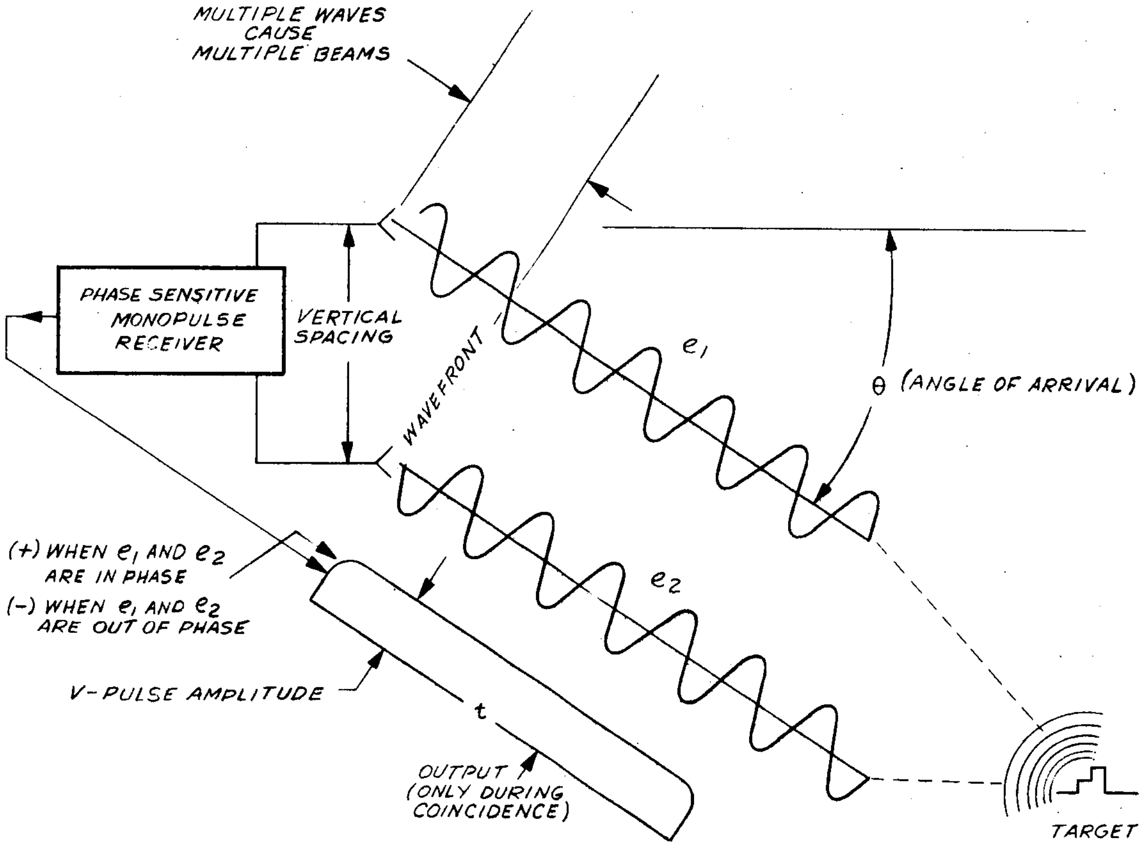


Figure 2. Monopulse Interferometer Principle

The depression angle θ, or the boresight offset angle is related to the altitude and range to the terrain as:

$$\sin \theta = \frac{A}{R}$$

and combining with the voltage relations,

$$V = \sin\left(\frac{DA \sin \theta}{R}\right)$$

for small angles this reduces to

$$V = \sin\left(\frac{DA}{R}\right)$$

The preceding voltage relations for the interferometer system assume only flat terrain and no pitch of the aircraft. A more general expression follows, using the first term for the flat terrain condition and the second term for a mountain slope.

$$V = \Big[\sin\left(\frac{DA}{R}\right)\Big]_{R=A}^{R=R_M} + \Big[\sin\Big(D \overbrace{\sin\Big[\sin^{-1} \frac{A' \operatorname{Cos} \beta}{R} - \beta\Big]}^{\phi}\Big)\Big]_{R=R_M}^{R=\infty}$$

Where A' would be the altitude if the mountain slope were extended to below the aircraft and the flat terrain did not exist. The terms are defined as:

$+ \theta$ = Down angle with respect to aircraft boresight

$- \theta$ = Up angle

$+ \beta$ = Upward tilt of ground plane

R_M = Range to mountain

R = Range

or

$$V \approx \Big[\sin\left(\frac{DA}{R}\right)\Big]_{R=A}^{R=R_M} + \Big[\sin\Big(D \sin\Big[\frac{A + R_M \beta}{R} - \beta\Big]\Big)\Big]_{R=R_M}^{R=\infty}$$

For small mountain slopes
(20° is high for average terrain)

$$V \approx \int_{R=A}^{R=R_M} \sin\left(\frac{DA}{R}\right) + \int_{R=R_M}^{R=\infty} \sin\left[D \sin 57.4 \left(\frac{A-\beta R}{R}\right)\right] \qquad \beta \text{ in radians}$$

The system output voltage is plotted as a function of range for figures 3, 4 and 5. The change in the voltage waveform is shown with altitude and attitude.

D. Real World Vertical Sweep Generation

The vertical sweep for the vertical display is derived from the range and voltage information shown in the previous section (C). The sweep is initiated when the first positive target is received in the vicinity of the nine degree depressed beam, and the slope of the sweep must depend on the frequency (or period) of the voltage waveform and the range (or time). This relation is expressed

$$\alpha = \frac{R\mathcal{E}}{\Delta R} = V$$

Where α is the small acute angle that the impinging energy forms with the slope of the terrain. α is not a measure of the angle between the aircraft longitudinal axis and the terrain, although it may be the same for the special case where the axis of the aircraft and the plane of the flat ground are parallel. However, the two angles are always proportional. $\mathcal{E}$ is the beam width (of one lobe in the region of dead ahead) and ΔR is the increment of range between the crossover points in the vicinity of the observed beam. (Crossover is defined as the change of the voltage output from plus to minus.) This expression defines a voltage with a slope proportional to the ratio of the range to the period of the return signal. The voltage is clamped to zero until the first return from the nine degree down beam is received. Figure 6 shows a typical sweep voltage and the effect of a mountain on that slope.

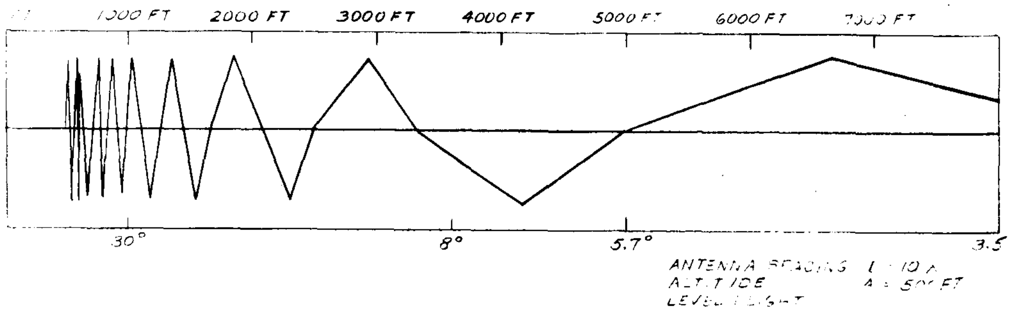


Figure 3. System Output as a Function of Slant Range, Alt. 500 Ft.

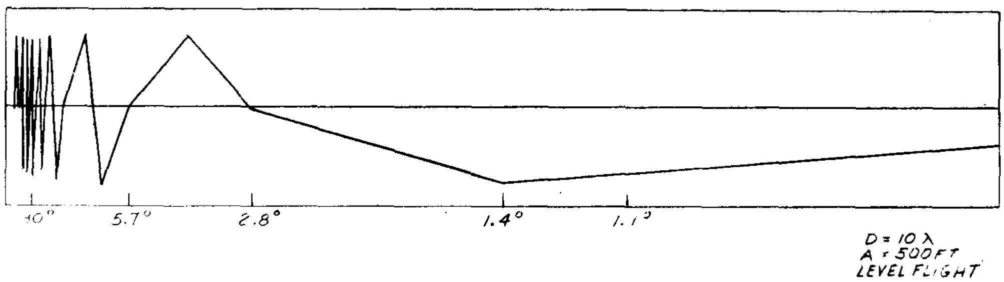


Figure 4. System Output as a Function of Slant Range, Alt. 100 Ft.

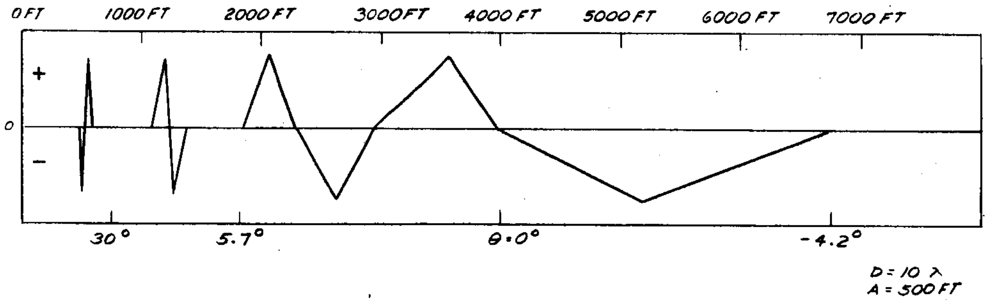


Figure 5. Voltage Output as a Function of Slant Range with the Aircraft Diving 10°

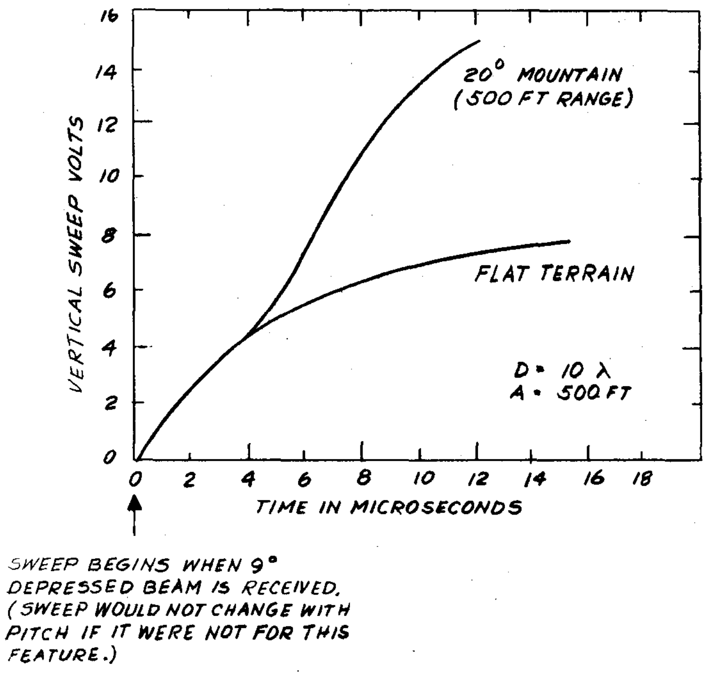


Figure 6. Vertical Deflection Voltage as a Function of Time

4.4 Signal Processing Circuits

VERTICAL SWEEP CIRCUITS

The vertical sweep circuits are composed of two major parts; the synthetic sweep and the interferometer comparator. These two circuits function together to present radar terrain returns in a proper perspective (angular position) on the vertical display.

The synthetic sweep operates during the absence of radar terrain signals. When radar returns are received, the interferometer comparator circuits over-ride the synthetic sweep and acquire control of the vertical display.

The synthetic sweep generates a waveform corresponding to a mathematical case of flat earth. It operates using a priori assumptions of the terrain characteristics, i.e., that the terrain is flat unless there is information to the contrary. This is consistent with the predicted behavior of terrain radar returns. Flat terrain will most often cause signal to be lost. The low angles of incidence may cause most of the transmitted energy to be reflected away from the aircraft.

Large obstacles, on the other hand, are generally good radar targets and signals can reasonably be expected from a statistically large number of them. When this situation occurs, then the comparator will over-ride the a priori assumptions of the synthetic sweep and will position the returns according to their measured angle of arrival. The interferometer comparator counts the number and rate of the interferometer beams received by the two antennas and is capable of determining the elevation angle of arrival of the radar returns. If signal should be momentarily lost while the vertical sweep is under control of the interferometer comparator, then the synthetic sweep will resume control. In this manner the synthetic sweep and interferometer comparator operate together to position the vertical sweep in accordance with the available information. If terrain characteristics were such that it could be relied upon to always give usable radar returns then there would be no need for the synthetic sweep. Since this is not the case, the synthetic sweep was created to supplement the angle of arrival information derived by the interferometer comparator. See Figure 7.

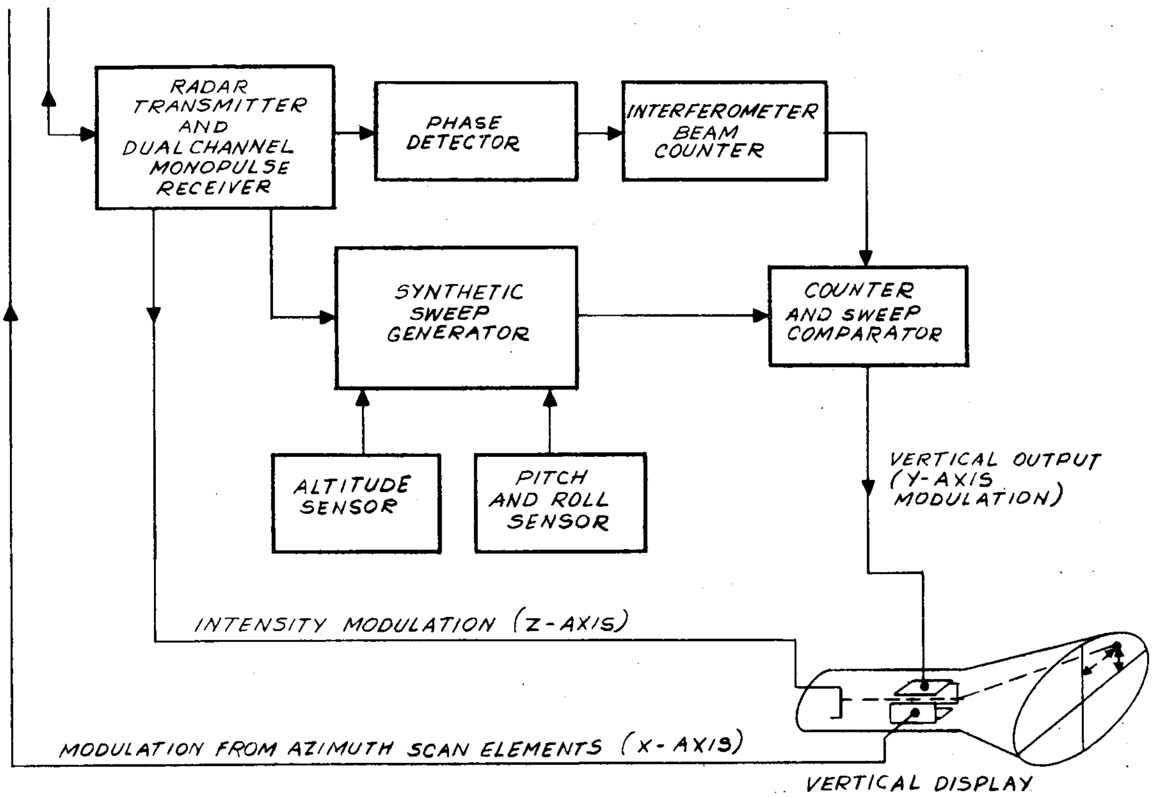


Figure 7. Three Dimensional Radar, Block Diagram

SYNTHETIC SWEEP

Function

The synthetic sweep is a solid state function generator which generates the proper vertical sweep waveform for the particular case of flat terrain. It also serves as a reference voltage and is compared in the interferometer comparator circuits to determine if the actual returns received by the radar correspond to the flat-earth case. If the returns differ (as they usually will) then over-ride circuits transfer control of the vertical sweep from the synthetic sweep to the interferometer beam-counter circuits. As long as the beam-counter circuits are receiving radar returns they maintain control of the vertical sweep.

Theory of Operation

The synthetic sweep generates a voltage which is proportional to the elevation angle of arrival for the case of flat terrain. From the geometry, this voltage has the form:

$E(t) = \theta(t) = \arcsin -2A/ct$

θ angle of arrival as measured from the horizon

For small angles ($\theta \leq 14°$)

A = absolute altitude
c = speed of light
t = time where t lies between

This can be simplified to
$E(t) = -K2A/ct$
with less than 1% error

$$\frac{2A}{c} \leq t \leq 00$$

This function can be approximated over the region of interest by a simple R-C charging network with an error of about 1°.[1]

---

1. To generate the arcsin function at the required speeds is difficult. Its shape is suggestive of an exponential risetime function. To accurately generate this function with a R-C or L-R circuit, however, the "time constant" must change as a function of time. This could be accomplished in several ways. One would be to use non-linear, R, C, or L elements. Another would be to use three-terminal elements whose values could be controlled by an external voltage. Another way would be to approximate the curve by step-wise increasing the time-constant by means of hold-off diodes. Since the vertical error is less than 1° when a simple R-C function generator is used, the additional complexity introduced by any of these methods did not appear to warrant their use at this stage of development.

To maintain a proper vertical display during aircraft maneuvers, the basic vertical sweep waveform must be modified by inputs from altitude, roll, and pitch sensors. These functions are accomplished as shown in the block diagram, Fig. 8. The waveforms during a typical vertical profile are shown in Fig. 9.

Circuit Description and Operational Sequence

Sync. Pulses from the magnetron trigger a 10 microsecond one-shot multivibrator at time t_o. The square-wave output is integrated to a linear ramp and is applied to one side of the altitude voltage comparator. The ramp is compared to a reference d-c voltage that is proportional to altitude. When the ramp exceeds the reference voltage (t_1), it triggers the 100 microsecond vertical sweep multivibrator.

A. Exponential Sweep

This voltage is applied to a transistor gate which closes and initiates the exponential sweep. The rise time of this waveform is controlled by an altitude operated R-C network, whose time constant increases with increasing altitude.

B. Pitch Control

The sweep is applied to the pitch voltage comparator where it is referenced against a d-c voltage proportional to aircraft pitch attitude. When the sweep exceeds the pitch bias (t_2), the comparator amplifies the difference between the two voltages and applies the output to the roll modulator. If the aircraft pitches upward, the pitch bias will increase causing the output of the synthetic sweep to decrease. If the aircraft pitches downward, the bias will fall and the output will increase.

C. Roll Modulator

Roll modulation is accomplished by varying the amplitude of the vertical sweep waveform as a function of antenna azimuth beam position. The depth of modulation is proportional to roll angle. At zero degrees roll, there is no modulation and all pulses are of equal amplitude. At 90° roll the modulation would be 100%. In the present system, however, the modulation is limited to about 50% allowing a roll capability of $\pm 37°$. (See Fig. 10).

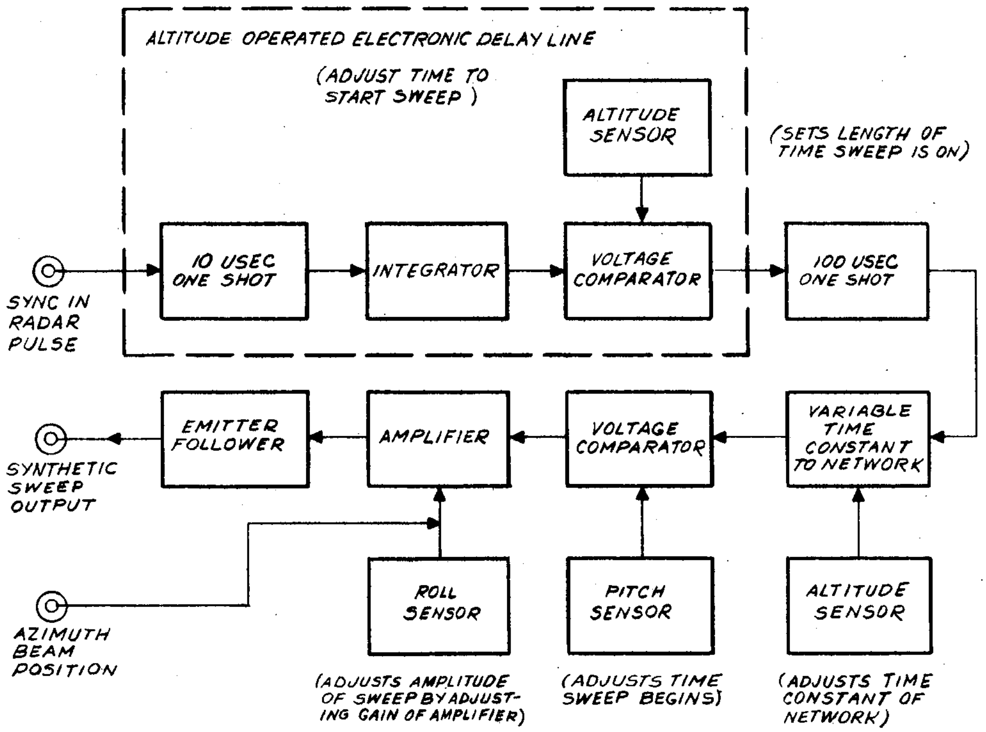


Figure 8. Synthetic Sweep Generator, Block Diagram

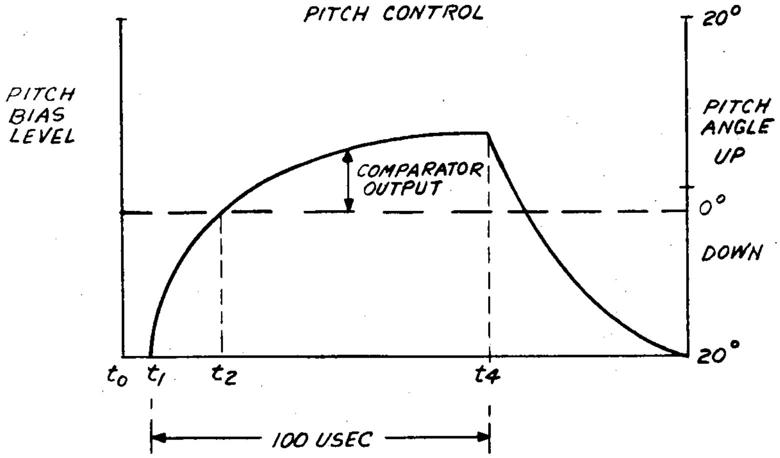


Figure 9. Pitch Control

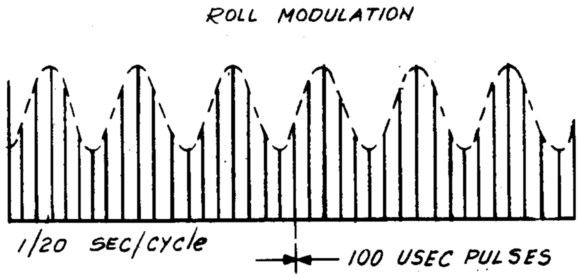


Figure 10. Roll Modulation

D. Output

The output of the roll modulator is applied to an emitter follower buffer, to provide isolation between the synthetic sweep and the interferometer comparator circuits.

INTERFEROMETER COMPARATOR

Function

The interferometer comparator modifies the synthetic sweep voltage according to information derived from radar terrain returns, and causes returns from non-flat terrain to be presented on the display at the proper position.

Theory of Operation

The interferometer comparator operates as an interferometer beam counter. Interferometer beams are caused by phase differences arising from unequal path lengths from a target to the two receiving antennas. Radar returns from targets lying in a region where the path difference to the two receiving antennas is between n and n + 1 half wavelengths will produce phase detector output pulses of the same polarity.[2] Returns from adjacent beams produce pulses of opposite polarity. The angle subtended by such a region from the aircraft constitutes an interferometer beamwidth. If the antennas are spaced 30 wavelengths apart these beams are very nearly to 1° wide in the region of interest (0 to $\pm 20°$ in elevation).

The interferometer comparator determines the rate the phase detector output is changing polarity. This is the rate that the interferometer beams are being received. It computes this rate in a analog manner and compares the actual rate with the reference rate, computed for flat terrain by the synthetic sweep. If the actual rate exceeds the reference rate, indicating that the terrain is not flat, then the comparator will

2. n is an integer 0, 1, 2. . . . n; it may take on any value up to n max, equal to 2d, where d is the antenna spacing in wavelengths. If n is odd the phase detector output will be of one polarity; if n is even the output will be of the opposite polarity.

modify the synthetic sweep waveform so as to properly position the radar returns on the display. The comparator will position the returns to a resolution of one elevation beamwidth (approximately 1°). By modifying the circuitry, this technique can extend the resolution if necessary. However, the positioning accuracy of one degree was considered adequate to demonstrate that the concept and techniques of the comparator method were valid.

Method of Operation

A simplified block diagram of the interferometer comparator and its relationship to the synthetic sweep is shown in Fig. 11. This figure indicates how the comparator modifies the synthetic sweep waveform as it receives information from the phase detector. A typical operational sequence for a single profile is also illustrated in Fig. 11 and in more detail in Fig. 12. The sequence is initiated by the receipt of the modulator trigger pulse from the magnetron. After a suitable delay (determined by the absolute altitude) the synthetic sweep begins deflecting the CRT spot upward at time t_o. At t_1 the comparator detects a change in the polarity of the phase detector output and begins counting these changes. At t_2 the counter stops counting due either to terrain with negative slopes or areas of very low reflectivity. The synthetic sweep regains command of the sweep voltage and the sweep proceeds on synthetic. The over-ride of the synthetic sweep resets the counter to zero. At t_3 the comparator again senses a polarity change in phase detector output pulses. The comparator begins counting beams at a much faster rate than the computed rate, indicating the presence of an obstacle. Counting continues until the radar horizon is reached, which in this case is above the flat earth horizon. The sweep remains at this point until it is returned to the bottom by the termination of the 100-micro-second one-shot pulse from the synthetic sweep. The beam counter is also simultaneously reset to zero and the signal processing circuits are ready to operate on the next transmitted pulse.

In this manner, the vertical profile places the radar returns in their proper perspective on the display.

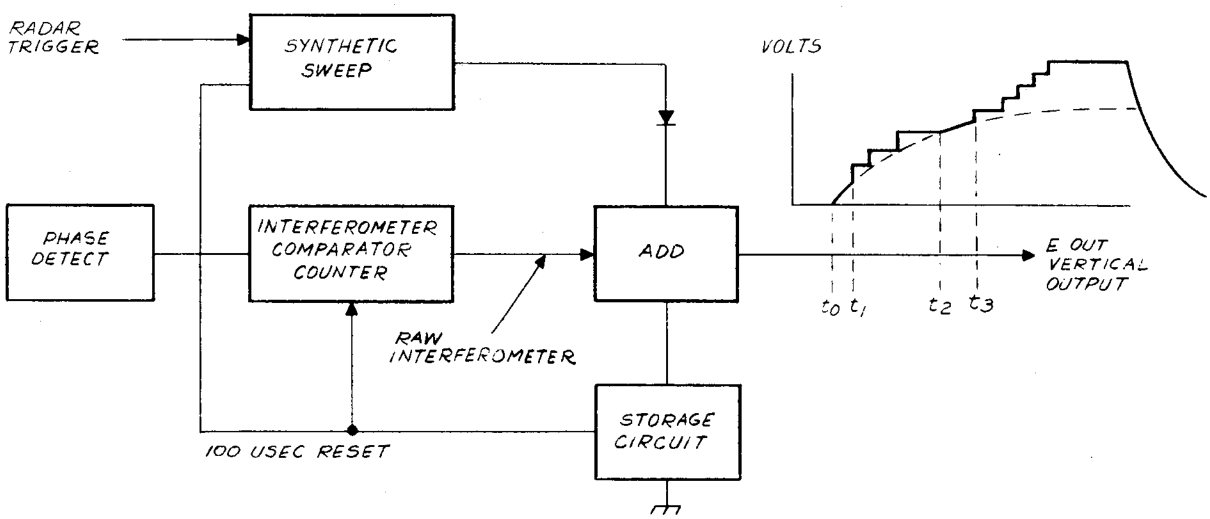


Figure 11. Vertical Sweep Computation, Simplified Block Diagram

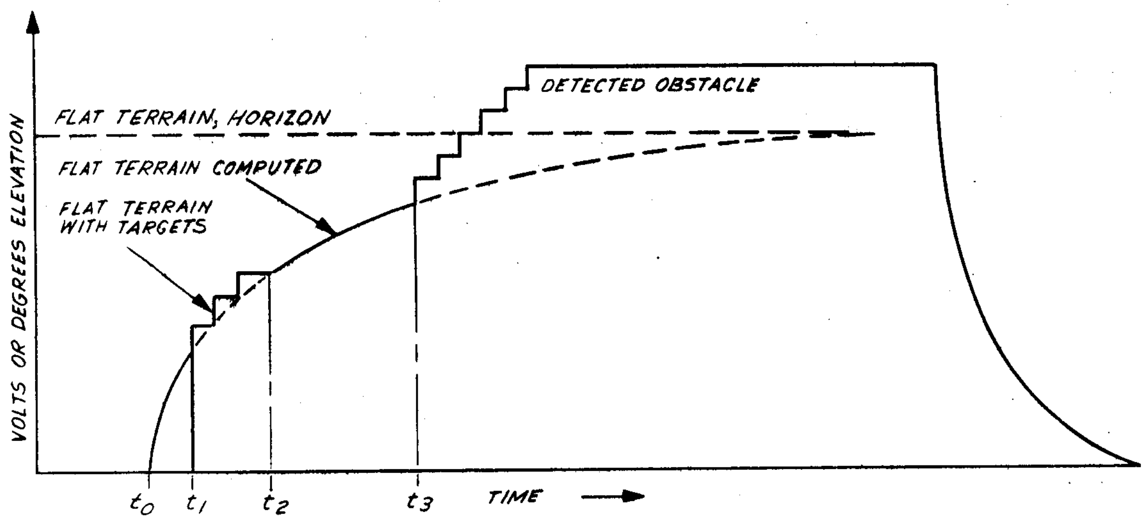


Figure 12. Three Dimensional Radar, Vertical Output

Circuit Description

A detailed break-down of the block diagram is shown in Fig. 13. The operation of these circuits are as follows: Bipolar pulses from the phase detector are applied through a Go-Gate that is enabled by the synthetic sweep. The gate prevents the comparator from counting beams until the synthetic sweep begins operating. This is done so that the counter circuits will not be overloaded by trying to count the rapidly occurring beams in the region below -20°.

Upon emerging from the gate, the pulses are amplified by a paraphase amplifier and sent into one of two channels depending upon the pulse polarity. Each channel has provisions for separate gain and threshold control to remove any asymmetries in pulse amplitude due to phase detector unbalance. Dual channel control also allows independent settings for sensitivity and noise level. The clipped and amplified pulses are applied to the Schmitt triggers which shape and limit the trigger pulses to the counter circuits.

The 16 state counter consists of four high-speed serially connected transistor binaries. One binary is connected to the two channels and it changes state each time the phase detector pulses change polarity. The changes of the first binary are propagated to the other three by means of high-speed gates. The four binaries count in the number of beams received. The four outputs of the counter are amplified and limited to a constant voltage and applied to a 3 stage Kirchoff adder. Flip-flop pairs #1 & #2 and #3 & #4 are first added together and then these two outputs are combined in a third adder. In this manner the binary digits stored in the counter are converted to an analog voltage. The output of the third adder is the 16 step stair-case analog waveform whose slope (number of steps per unit time) represents the rate at which interferometer beams are being received.

The output of the adder is compared with the synthetic sweep in the comparator-adder circuits. Whenever the counter begins counting beams, it momentarily assumes control of the vertical sweep. This is done by step-wise adding the value of one count to the value of the

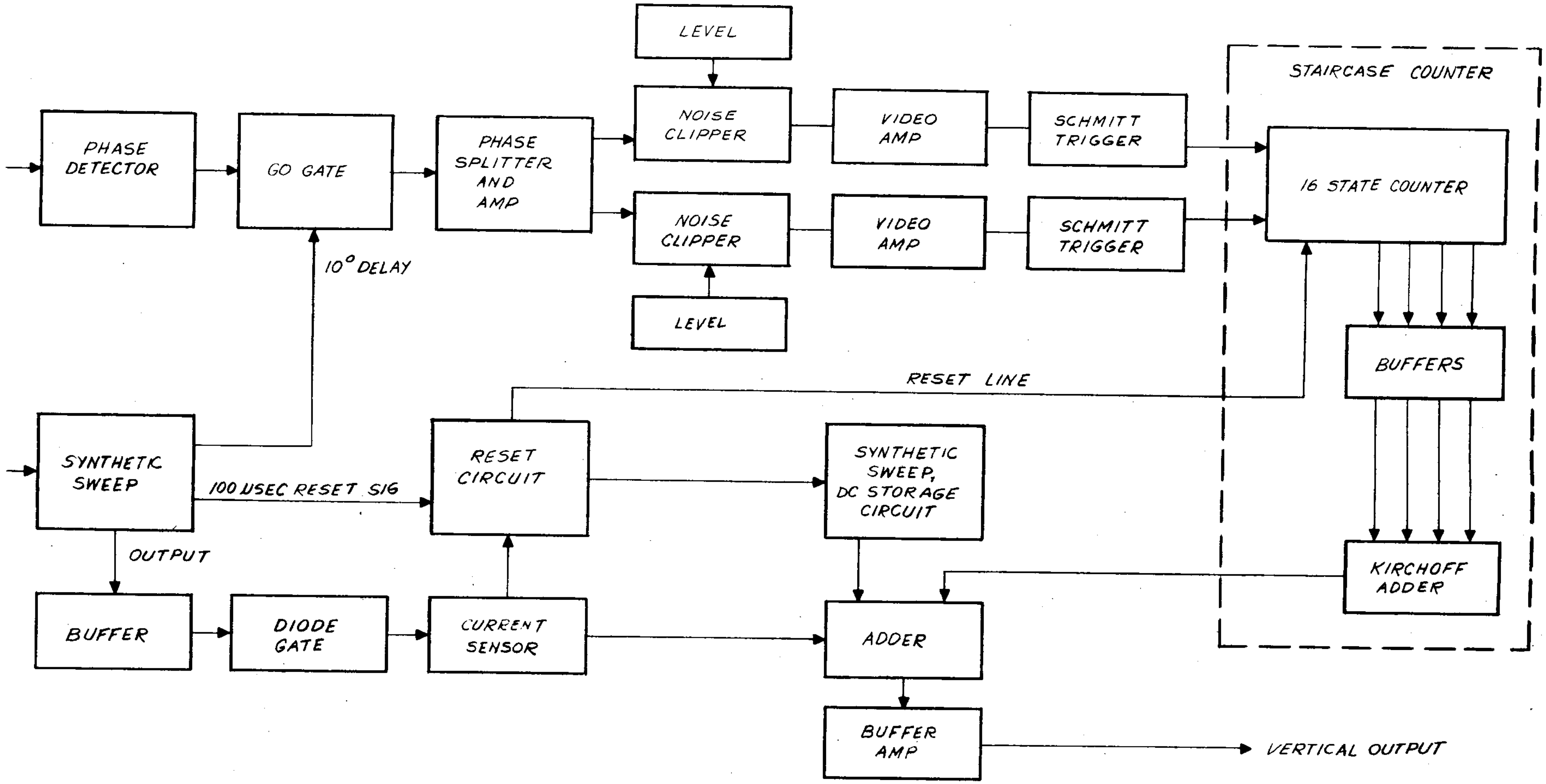


Figure 13. Development of Vertical Sweep (Interferometer Beam Counter and Synthetic Sweep Generator)

synthetic sweep voltage at the time the counter begins counting. As long as the counter is counting beams in excess of the rate as computed by the synthetic sweep for flat terrain, it retains control of the sweep voltage. However, if the counter ceases to count (such as at time t_2 in the previous example) the synthetic sweep regains control whenever its value exceeds that of the beam counter (time t_3 in the example). At this time the counter is reset to zero by means of the current sensor and reset circuits. Presetting the counter each time the sweep control reverts back to the synthetic sweep causes the effective counting range of the counter to be extended. Without reset, the counter could correctly count only 16 beams. With reset, the counter can correctly count any number of beams, provided there are no more than 16 in any one consecutive sequence.

The output of the comparator-adder is sent to a buffer stage and then applied to the input of the vertical deflection amplifier.

Circuit Design Considerations

The function of the interferometer comparator could have, no doubt, been accomplished in several different ways. As with any electronic circuitry of this magnitude of complexity, there are several different methods which could have been used to satisfactorily perform the required function. The following is a brief discussion of the considerations given to the design of the various portions of the interferometer comparator:

1. Phase Splitter

   In the design of the phase splitter circuit, consideration was first given to using a differential amplifier. This configuration was selected for independent gain settings of the two outputs and because it offered two outputs of equal impedance. This configuration was found to have uncontrolled phase shift between the two outputs due to differences in transistor parameters. The result was that counter triggering problems occurred due to unequal delays in the two channels. A paraphase amplifier was substituted in its place and this reduced the phase shift to an acceptable value.

2. Sensitivity and Threshold Circuits

The wide variety of signals that could be expected from the phase detector presented potential problems of D.C. bias level changes with changing input signals. Careful choice of coupling methods were required to prevent sensitivity and threshold levels from changing over the expected dynamic range of input signals.

3. Counter Circuits

Several types of counter circuits were considered for this application. One was a magnetic core counter and three were transistor binary counters. The magnetic core counter was rejected despite its potential low cost on the basis that available cores would not operate reliably at the required speeds.

The three types of transistor counters considered differed in the method used to keep the binaries from saturating. Non-saturating binaries were considered necessary if inexpensive transistors types were to be used. The three methods considered were:

a) Zener diode clamping
b) Forward biased diode clamping
c) Current mode switching

The zener diode clamping method offered the least design problems but was the most expensive method since the zener diodes cost about twice as much as the transistors. The second method, using forward biased diodes, was less expensive but this method reduced the switching speed of the transistors below a usable value. Current mode switching is the least expensive of the three types considered, but is is more difficult to design due to the additional constraints imposed upon the circuit designer. After some cut-and-try, this method was successfully employed with good results.

Two types of coupling circuits were considered for triggering the four binary stages. R-C differentiating networks with steering diodes were first attempted. This was found to be unsatisfactory due to losses in the differentiating networks which caused the trigger amplitudes to be marginal. Transistor-diode and gates were then tried. These functioned very well, and also served a dual function as buffers between the counter binaries and the adder stages.

4. Adder Circuits

Two types of adder circuits were considered: Diode matrix adders and Kirchoff adders. The diode matrix adders were rejected on the basis of cost. A 16 state matrix would require 32 diodes $\frac{(N \cdot 2^N)}{2}$ plus another 16 diodes to add the propositions together, making a total of 48 diodes required. The cost of this approach would be about twelve times higher than for Kirchoff adders.

HORIZONTAL SWEEP CIRCUITS

The horizontal sweep circuits perform the relatively simple task of transmitting the antenna azimuth beam position information to the P. R. F. FM circuits, horizontal deflection amplifiers, and the synthetic sweep roll modulator circuits.

ANTENNA AZIMUTH BEAM POSITION

Theory of Operation

The antenna azimuth beam position is a linear function of the ridge drive shaft angular position. To transmit the antenna azimuth beam position to the required circuits, a sensor whose output is proportional to ridge drive shaft position is installed on the driving motor. This sensor may be either a sine-cosine continuous turning potentiometer or it may be a Resolver positioning device commonly used in servomechanisms applications. A synchro transmitter may also be used if it is connected properly. This latter method was used in the system because of its low cost and availability.

Circuit Description

The block diagram of the horizontal sweep circuits is shown in Fig. 14. The oscillator-power amplifier combination provide excitation for the synchro-transmitter. The output of the synchro is a a-c waveform that is amplitude modulated as a function of the motor drive shaft position.

This is then applied to the demodulator-filter network where the modulation is removed from the carrier. The modulation waveform consisting of a 20 cps sine wave is then amplified and sent to the horizontal deflection circuits, PRF-FM circuits, and Roll modulator. Sine-cosine potentiometers were originally installed as the angular sensor. This method appeared initially attractive because of its simplicity, in that the exciter-amplifier and demodulator-filter circuits would have been unnecessary. The method was soon abandoned, however, when it became apparent the sine-cosine potentiometers had very high failure rates at the high scanning speeds employed.

P. R. F. FREQUENCY MODULATION CIRCUITS

Function

The P. R. F. frequency modulation circuits equalize the information content across the face of the C. R. T. display.

Perhaps the best way to explain the function of the P. R. F. is to examine the display characteristics that would occur if the radar transmitted at a constant P. R. F.

The sinusoidal antenna azimuth scan causes the azimuth beam to spend more time at the edges of the displayed area than it does at the middle. This causes the vertical sweep lines to be unequally distributed across the display. They would be "bunched up" at the edges and be sparse in the center. The information content of the display is then greater at the edges than the center, an undesirable situation. (It is assumed that the pilot desires the most information in the direction he is going rather than 20° or 30° either side of the flight path.)

To overcome this effect, the P. R. F. of the radar is varied as a co-sinusoidal function of the look angle. The P. R. F. is highest at the center of the display (where the beam is moving fastest) and lowest at the edges (where the beam is slowing down and turning around). By doing this the P. R. F. varies as the rate of change of scan angle, $d\theta/dt$, and the number of pulses per degree of scan are constant over the entire field of view. Since there is one vertical sweep line transmitted per pulse, the sweep lines are spaced equidistant across the CRT display.

P.R.F. - FM CIRCUITS

Circuit Description (See Figure 15)

The cosinusoidal waveform from the horizontal sweep circuits is applied to a self-balancing paraphase amplifier and then full-wave rectified. The full-wave rectified output is then applied to the control grid of a cathode-coupled free-running multivibrator whose frequency of oscillation is proportional to the control grid voltage. The output of the multivibrator consists of frequency modulated square waves, whose duration is proportional to the amplitude of the grid waveform. The square waves are differentiated and the positive spikes are applied to a trigger blocking-oscillator in a conventional gas-tube magnetron modulator circuit.

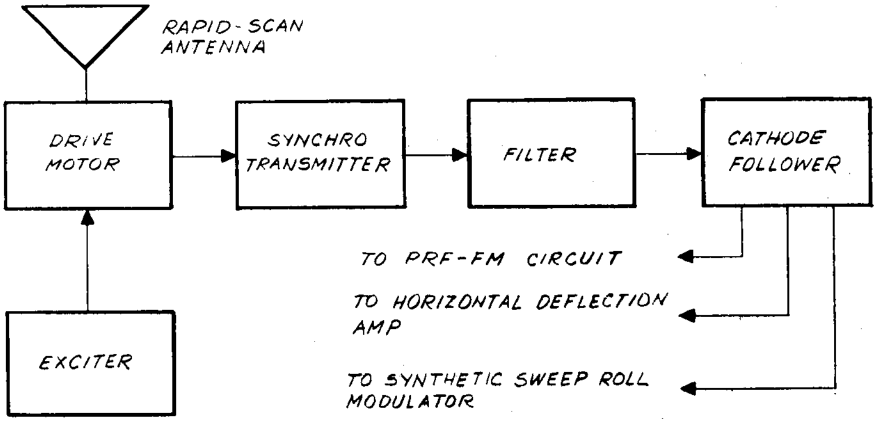


Figure 14. Horizontal Sweep Circuits, Block Diagram

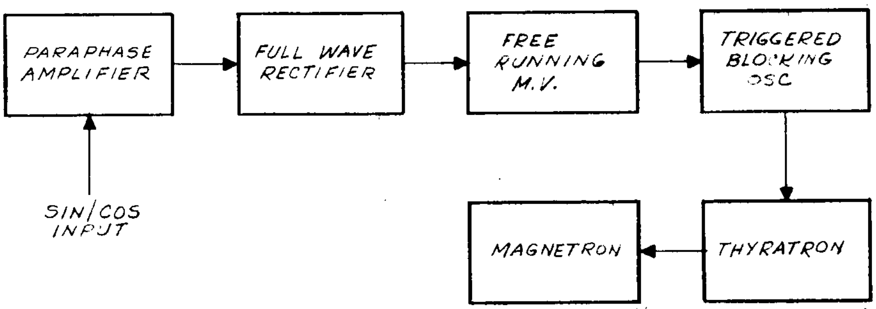
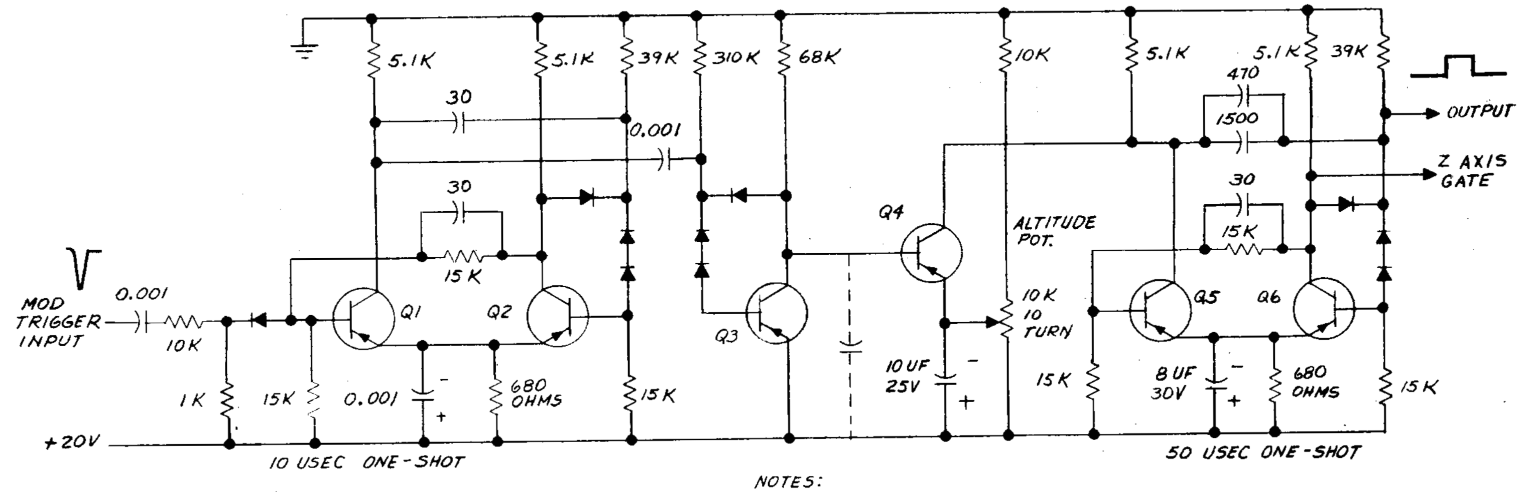


Figure 15. PRF-FM Circuits, Block Diagram



NOTES:

1. UNLESS OTHERWISE SPECIFIED,
   A. ALL TRANSISTORS 2N643.
   B. ALL DIODES IN38A
   C. ALL RESISTERS 1/4 W
   D. ALL CAPACITANCES IN PF.

Figure 16. Preliminary Schematic, Synthetic Sweep Generator (Sheet 1 of 2)

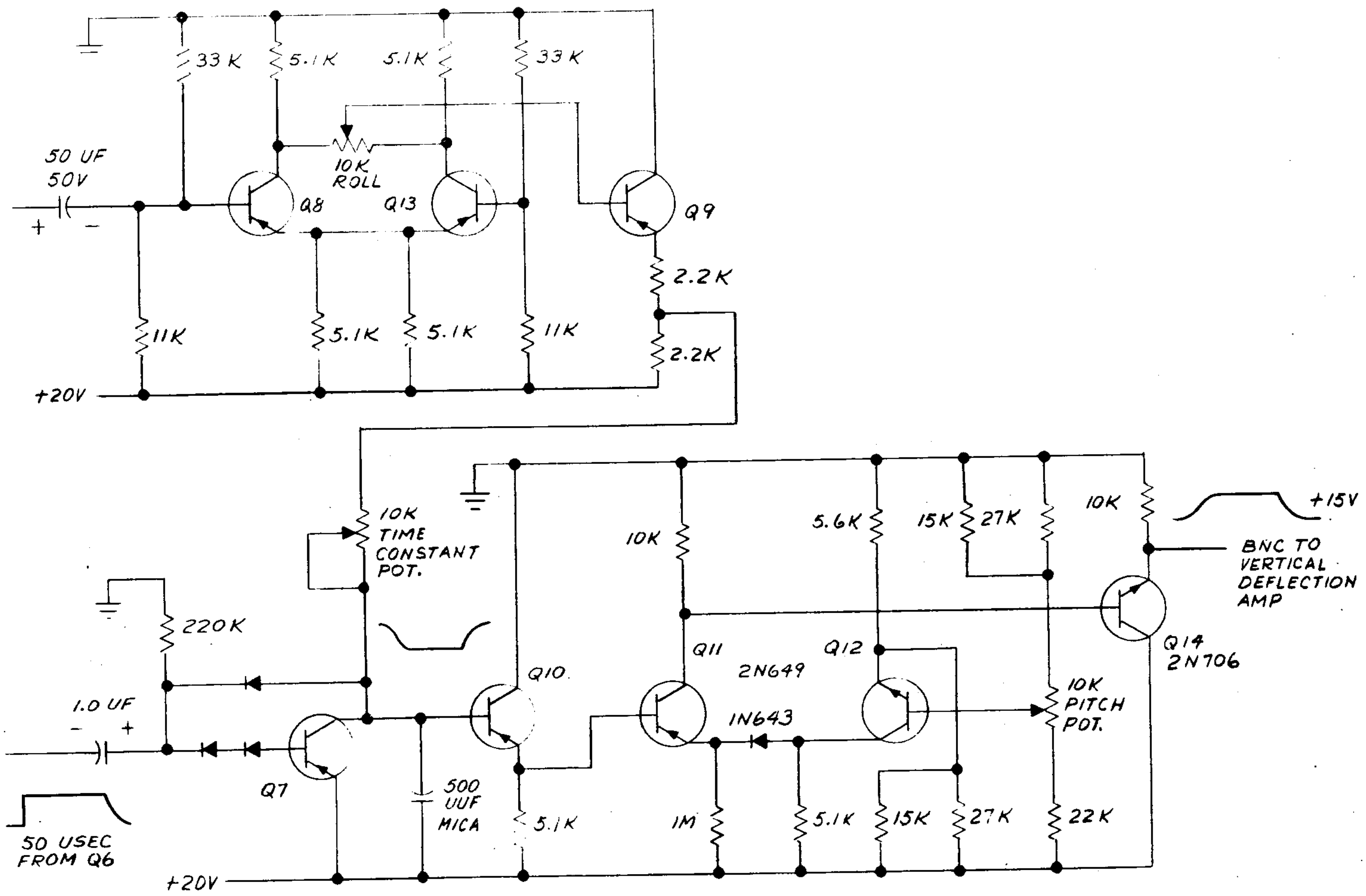


Figure 17. Preliminary Schematic, Synthetic Sweep Generator (Sheet 2 of 2)

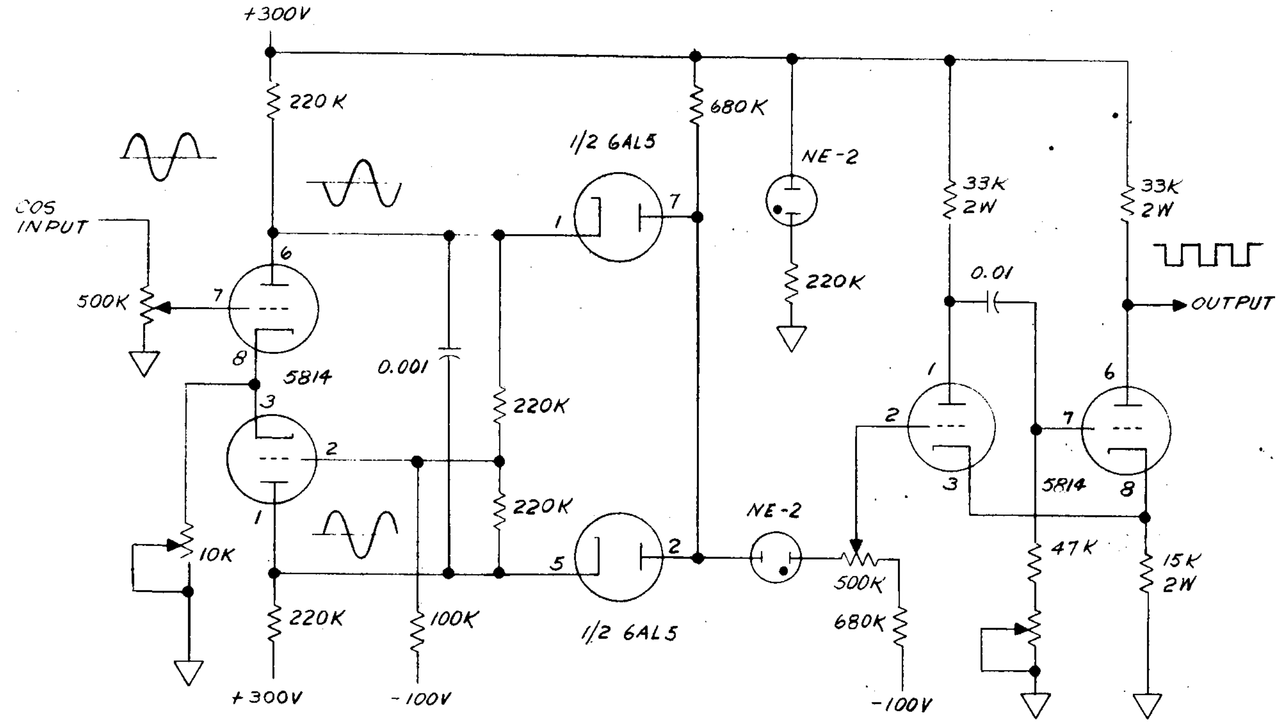


Figure 18. PRF-FM Circuit

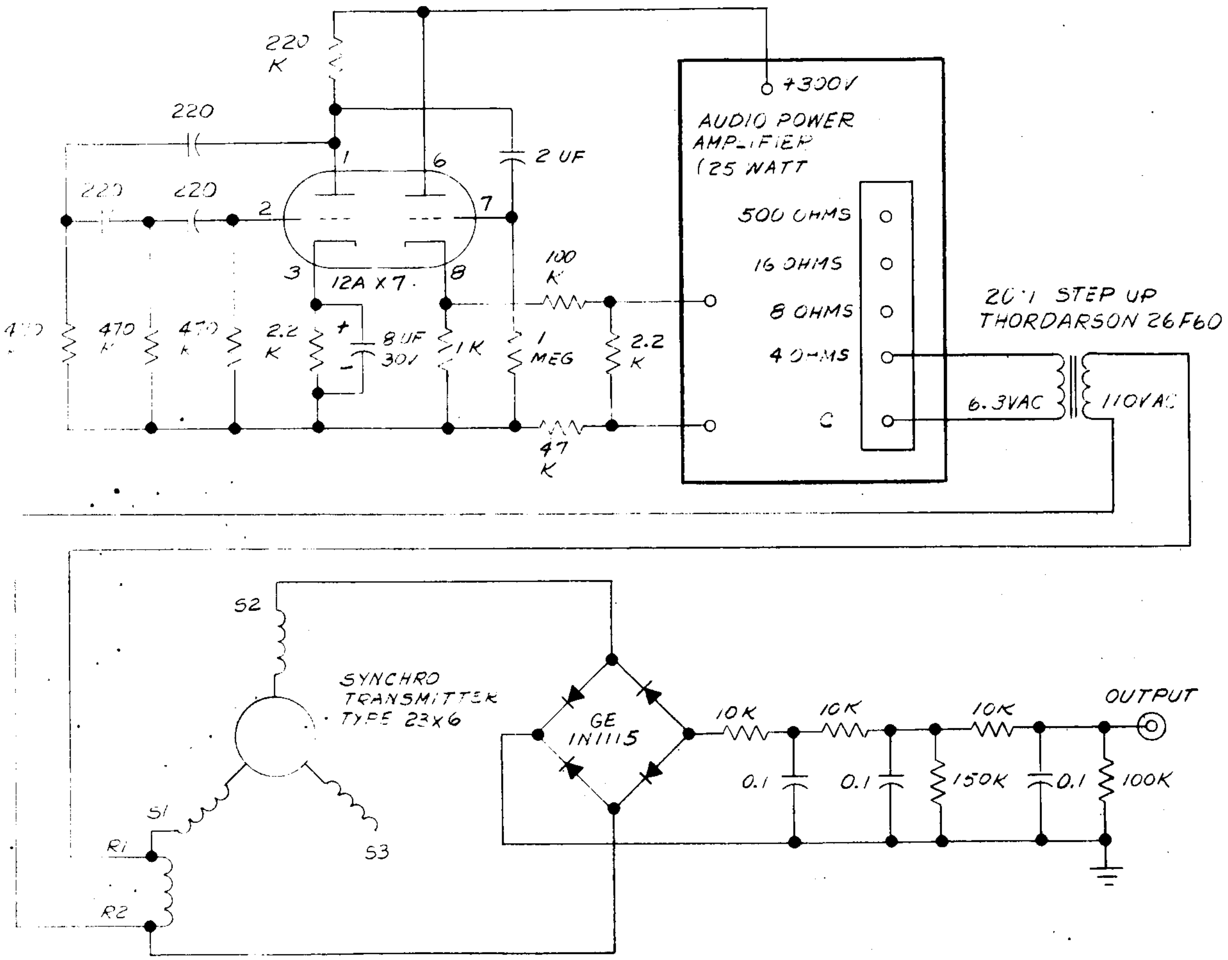


Figure 19. Synchro Function Generator

6.1 IMPROVEMENT OF VERTICAL RESOLUTION

By electrically rotating the plane of the antenna array as a function of the phase history of the radar return, a large improvement vertical resolution can be obtained. A means of doing this is shown in the block diagram in Fig. 20. A phase shifter rotates the plane of the antennas as a function of time. The system functions as a type of phase tracking loop. The electrical boresight of the antenna array is made to track the phase center of the radar terrain returns as a function of time. The system operates as follows:

Consider the phase shifter in the diagram as being an electrically controllable line stretcher. After each transmitted pulse, the phase shifter begins sweeping the boresight axis of the antennas upward from some initial depression angle of approximately -30° to -45°. The boresight axis is rotated at a rate corresponding to the motion of phase center from flat terrain returns. If the terrain is flat, the motion of the boresight axis coincides with the moving phase center, and the output of the phase detector is zero. If the terrain is not flat, the motions of the boresight axis and of the phase center are not synchronous and a difference of phase exists between the signals at the two antennas. The phase detector senses this and will produce an output voltage proportional to the error. The error voltage is fed back to the phase shifter and it drives the phase error to zero by modifying the sweep rate of the boresight axis. In this manner, the feedback loop is closed and the boresight axis of the antennas is forced to track the phase center of the terrain returns. The amplitude of the phase shifter control voltage is directly related to the angle the boresight axis makes with the horizon. It can be amplified and applied to the vertical deflection plates of the CRT display to properly position the radar returns.

The amount of resolution improvement that can be obtained with this system is dependent upon the tracking angular accuracy of the antenna plane. If, for example, the tracking accuracy is 3 electrical phase degrees, a vertical resolution of 1/60 degree would result if the existing 30 wavelength spacings were used. This would be an improvement of a factor of 60 over the original system. Conversely, if 1 degree resolution was considered to be adequate, this could be obtained with an antenna spacing of one half wavelength. This would place the antennas so close together that they would touch each other.

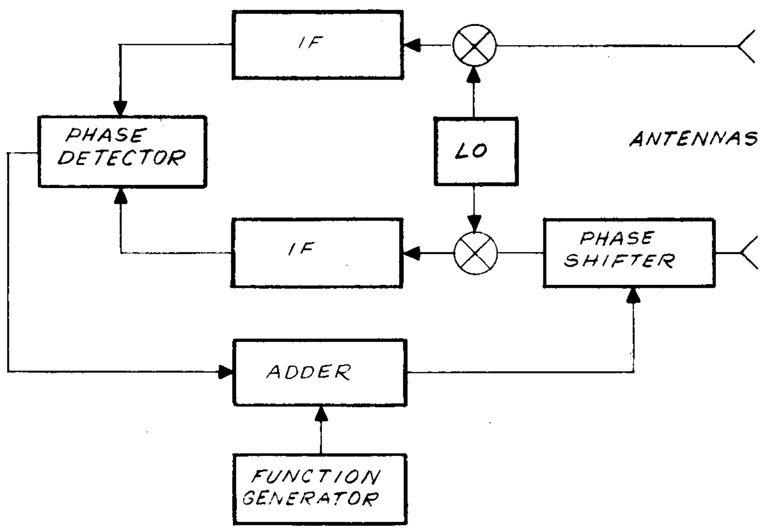


Figure 20. Phase Shift Method of Obtaining Higher Angular Resolution

This technique would add little complexity to the existing system. The Phase Shifter Function Generator would be a modified form of the Synthetic Sweep. The error voltage adder circuit would replace the Interferometer Comparator. The Phase Shifter would replace the Beam Counter Circuitry.

6.2 INTERFEROMETER TECHNIQUE USING THREE ANTENNAS

A three-element antenna array allows the use of a different technique for determining the angle of arrival of terrain returns. The advantages of this technique over the existing one is that the elevation angle may be determined without making any assumptions regarding the nature of the terrain and without counting and storing previously received information. The beam counting technique of the two-element array may sometimes be in error if the counter fails to count all the beams received, or if the terrain rises so sharply that the synthetic sweep has appreciable error before the interferometer comparator begins to function. The three-element array eliminates the possibility of such errors. It allows the system to operate correctly regardless of the types of terrain encountered.

The three-element system uses three antennas located so as to form a right triangular configuration. Two simultaneous sets of phase measurements are made on a returning signal, one from each of the two orthogonal pairs of antennas. The rate of change of phase of the two measurements will not be identical. As the angle of arrival of terrain returns changes, the phase detector output from each pair of adjacent antennas will change at differing rates. In a given period of time, one phase detector output will have more nulls (crossovers) than the other. This is due to the hyperbolic curvature of the equiphase contours. By comparing the outputs of the two phase detectors, the elevation angle of arrival can be determined without chance of ambiquity.

The system can be operated in a manner similar to the originally described interferometer technique (fixed antennas), or the two pair of antennas can be rotated electrically by means of two phase shifters to give the higher resolution characteristics described in Section 6.1

6.3 CROSSED BEAM

The interferometer beam counting method can be replaced by use of a rapidly scanning pencil beam. Such a technique has both advantages and disadvantages. The main disadvantage is that it requires a much higher radar PRF to cover the same area as the interferometer method. Each radar pulse now contains information pertaining only to one small area of the terrain, rather than containing information on a profile or line of terrain targets. In some cases this disadvantage will be more than compensated by the ability of the cross-beam system to discern all types of terrain in its proper angular position. It can do this without aid of other aircraft sensors, such as gyros, altimeters, etc.

A method of obtaining a rapidly scanning pencil beam is possible through the use of two rapid-scan antennas developed during this study. These antennas are arranged to form a cross or "X", similar in form to the Mills Cross Array.[1] In this arrangement, the transmitting and receiving antennas both have narrow "fan" beams, but the two beams are oriented at right angles to each other. Energy is received from the terrain only in the narrow region where the two beams overlap. Rapid-scanning of the two antennas causes the location of the intersection to move over the radar field of view. The terrain is printed out on the display in a point-by-point manner.

To gain an idea of what such a system might require, consider the following tentative specifications for providing all-weather, low-level mission capability to helicopters or light observation aircraft.

Resolution = 1° x 1°
Field of view = 30° x 30°
Frame Rate = 15 Frames/sec
Range = 1/2 mile

The required PRF is 30x30x30 = 27,000 pps.

Because of the limited range requirements, a peak pulse power of 1 to 10 kw will suffice. Taking the larger figure and a pulse width 0.1 μsec, the required average power handling capability of the magnetron is 27 watts. The duty cycle is 0.0027.

[1] A Microsteradian Antenna Array.

If a raster scan is used to cover the required area, then one antenna will scan at a rate of 15 cps, which presents no particular problems for the present ridge scanner. The other antenna will be required, however, to scan at 450 cps. To achieve this scan rate with the present design might be difficult, but the ferrite scanner or the dielectric scanner will be able to handle these rates without difficulty. The above requirements do not appear to present much difficulty. Consequently, such a radar appears to be well within the realm of feasibility.

6.4 VARIABLE RESOLUTION SYSTEM

A variable resolution system provides the pilot with a display whose resolution is a function of azimuth and elevation angle. Such a display has the highest resolution and gives the most information in the direction of the flight path. Resolution decreases as a function of angle off the flight path and information rate is a function of angle. Around the edges of the display where decreased resolution is acceptable, the PRF is quite low and the antenna scan-rate high. In the center of the display, where high resolution is desired, the PRF increases and the scanning beam slows down to paint a detailed picture of this portion of the display.

The simplest variable resolution system requires three features:

1. A method of controlling the PRF as a function of scan angle.
2. A method of varying antenna scan rate as a function of angle.
3. A method of increasing antenna beam width as a function of angle.

The first requirement, that of variable PRF, is not difficult to achieve. Once a voltage waveform corresponding to the desired PRF variation is obtained, the PRF is varied in a manner similar to that shown in the PRF-FM circuits of Section 4.4

The method of accomplishing the second requirement, variable scan rate, will depend on the type of antenna employed. To accomplish this with an all-mechanical, variable scan may prove difficult due to the required driving forces, resulting accelerations, and mechanical stresses. If the mechanical system proves difficult, the ferrite scanner or dielectric scanner can be used to eliminate some of the mechanical constraints. If these techniques are not adequate, then a combination scan employing electrical, mechanical and

and frequency techniques can be employed. With all of these techniques available, almost any type of scan pattern is possible.

The third requirement, that of increasing antenna beamwidth as a function of scan angle, requires that the size of the antenna aperture be varied. For a line source array, this means that the effective radiating length of the array must decrease as a function of scan angle. Some increase of beamwidth with scan angle is inherent in line source arrays. Other techniques that might be used to increase the beamwidth include use of ferrite switches, diode controlled short circuits, or ionized gaseous shorts. Further investigation will be necessary to select the technique(s) best suited for use in this application.

With the multiplicity of techniques available to fullfil the three requirements, a variable resolution system appears to be possible with modest increase in system complexity.

A useful additional feature of this system is the addition of a "joystick" control. This enables the pilot to move the region of high resolution around on the display. Areas of particular interest can be closely investigated, even though they are not on the flight path.

A more elaborate refinement, but one offering some very interesting possibilities, is a variable resolution system in which the location of the high resolution area corresponds to the point on the display at which the pilot is looking. Such a system matches the resolution of the display to the off-axis resolution characteristics of the eye (Fig. 21).

This requires the use of an "eyeball sensor", capable of determining the location of the region of foveal vision on the display. The development of such a sensor might present some engineering challenges, but does not appear to be impossible. The advantages of such a system are great, for now an optimum match is possible between the information rates in the man-machine system.

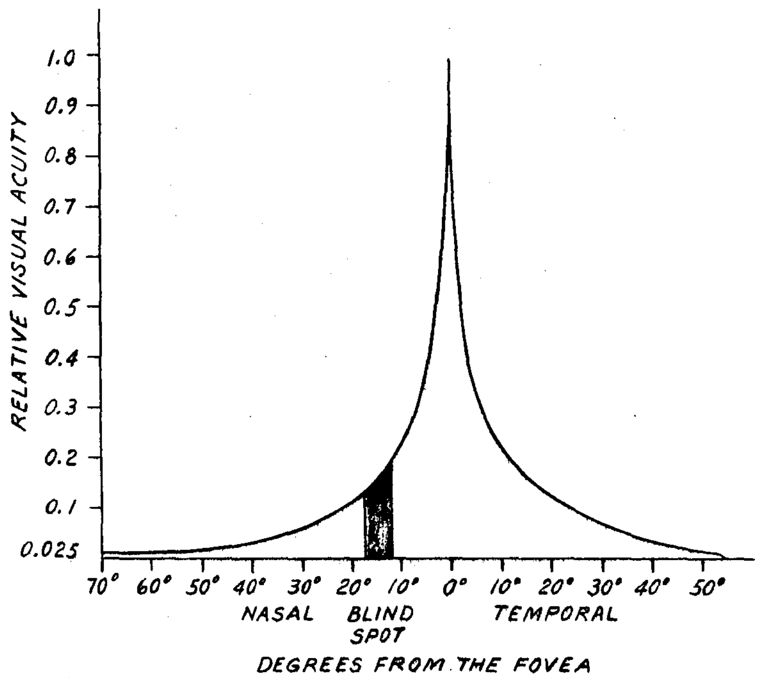


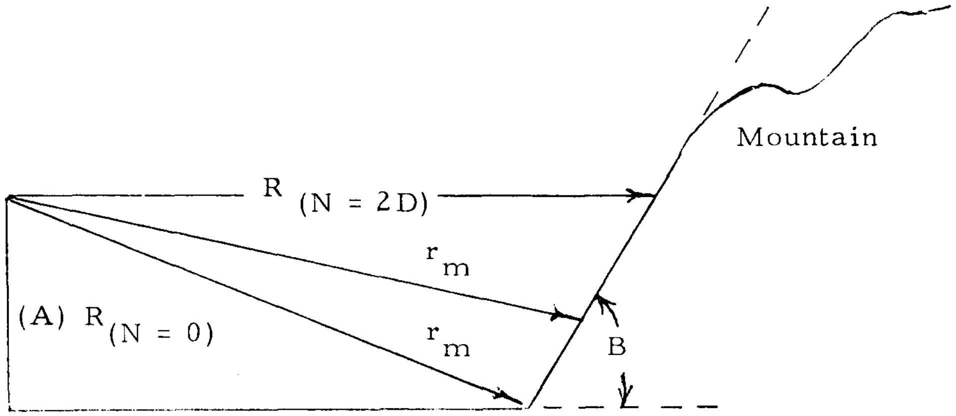
Figure 21. Curve of Daylight Visual Activity for Different Parts of the Eye[1]

[1] "How We See: A Summary of Basic Principles" by A. Chapanis, in Human Factors in Undersea Warfare

7. BASIC EQUATIONS (Interferometer)

A) THE RANGE (R) TO THE TERRAIN ALONG DISCRETE NULLS (N) OF THE INTERFEROMETER PATTERN IS:

$$(1) \qquad R_n - \frac{2D(A\cos B - \sin B)}{N\cos B - \sin B} \quad \frac{\sqrt{r_m{}^2 - A^2}}{\sqrt{4D^2 - N^2}}$$



Where

B = Slope of mountain
r_m = Minimum range to mountain
r_n = Slant range to mountain when the phase detector output is zero
D = Number of wavelengths
N = 1, 2, 3, 4, ...

And the following conditions:

(2) $-2D \leq N \leq 2D$

(3) $r_m - R < 00$

(4) $A \leq R \leq R_m$

(5) $r_m < R < 00$

B) <u>For B = 0 i.e., flat terrain, equation 1 reduces to:</u>

$$R = \frac{2DA}{N}$$

Where N has the significance of numbering beams up to the horizon.

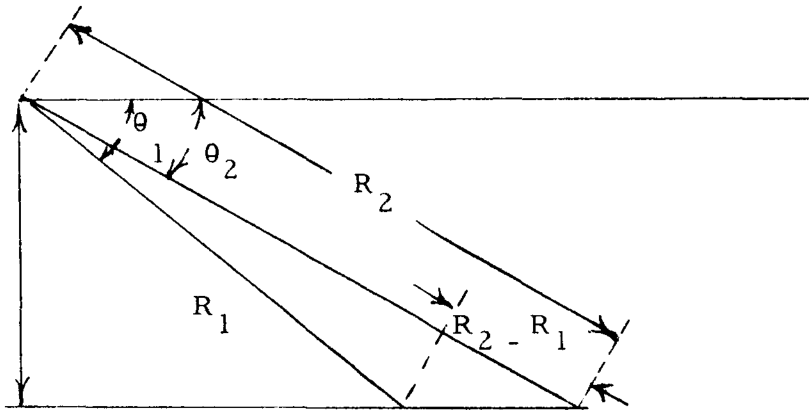
Example: N = 1 is 1st beam, N = 2 is 2nd beam, etc.

C) THE NUMBER OF BEAMS FROM THE HORIZON TO THE ALTITUDE LINE (0° to 90°) is equal to 2D where D is the number of wavelengths.

INTERFEROMETER PULSE WIDTH LIMITING ANGLE

D) INTERFEROMETER PULSE WIDTH LIMITING OCCURS WHEN THE LENGTH OF TWO ADJACENT BEAMS INTERSECTING FLAT TERRAIN EQUALS THE RADAR TRANSMITTER PULSE WIDTH.

$$R_2 - R_1 \approx 57.4A \left(\frac{\theta_1 - \theta_2}{\theta_1 \theta_2} \right)$$



Where

$\theta_1 - \theta_2$ = Interferometer angular null spacing

θ_1 = Angle at which pulse width limiting occurs

$R_2 - R_1$ = Pulse width measured in feet
(.1 μsec transmitted pulse = 50 feet)

Typical Example

If A = 100 feet, $\theta_1 - \theta_2 = 1^\circ$, and $R_2 - R_1$ = 50 feet, then the angle at which pulse width limiting occurs is:

$$50 \approx 57.4(100) \frac{\theta_1 - \theta_2}{\theta_1 \theta_2}. \quad \text{Also} \quad \theta_1 - \theta_2 = 1^\circ$$

Solving simultaneously, the pulse width limiting angle $\theta_1 = 11^\circ$

E) INTERFEROMETER BEAMWIDTH

$$\theta = \sin^{-1} \frac{\lambda r}{2D}$$ General, where θ = null spacing in degrees or beamwidth

for small θ

$$\theta = \frac{\lambda r}{2D} (57.4)$$